California Energy Commission

FINAL CONSULTANT REPORT

Forecast of Medium- and Heavy-Duty Vehicle Attributes to 2030

Prepared for: **California Energy Commission**
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ABSTRACT

This California Energy Commission report documents the forecast of vehicle fuel economy and price for medium- and heavy-duty vehicles for the 2016-to-2030 period and the technological and modeling assumptions used to derive the forecast. The Energy Commission uses transportation energy demand models that require projections of these vehicle attributes. The fuel economy and greenhouse gas emissions of medium- and heavy-duty vehicles are required to meet specific mandated levels by federal regulations through 2027 and beyond. Since the standards necessitate the use of more fuel-saving technologies than would otherwise be demanded by the market, the regulatory analysis developed by United States Environmental Protection Agency and National Highway Traffic Safety Administration (in support of the standards) is used extensively, though some modifications were made to derive the projections for the Energy Commission. This report also summarizes the technologies available to improve the fuel economy of trucks powered by conventional gasoline or diesel engines, as well as those using alternative fuels like ethanol, natural gas, electricity, and hydrogen. H-D Systems developed projections for two scenarios in this analysis.

Keywords: California Energy Commission, vehicle attributes, heavy-duty trucks, attribute forecast, fuel economy, alternative fuels

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EXECUTIVE SUMMARY

The California Energy Commission estimates fuel consumption in the transportation sector and projects the market penetration of alternative fuel vehicles as a part of the *2017 Integrated Energy Policy Report* and other state projects. To forecast these values, the Energy Commission uses transportation demand models that require projections of vehicle attributes for the 2016-to-2030 period. This report presents H-D Systems' forecast of medium- and heavy-duty vehicle fuel economy and vehicle prices, which are used as inputs into the Energy Commission's transportation models. The report also documents the technological and modeling assumptions used to derive the attribute forecast.

The second phase of the federal *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles* require medium- and heavy-duty vehicles to meet specific mandated fuel economy levels through 2027. The United States Environmental Protection Agency and the National Highway Traffic Safety Administration completed a comprehensive analysis of technological improvements available to improve fuel economy and reduce greenhouse gas emissions in support of the Federal Phase 2 regulations. The analysis by the agencies is documented in the Regulatory Impact Assessment of the federal Phase 2 standards. H-D Systems' forecast of vehicle attributes for the Energy Commission uses many elements of the standards derived in the Regulatory Impact Assessment.

The Energy Commission's transportation demand models require medium- and heavy-duty attributes by vehicle class and fuel type. Medium- and heavy-duty trucks are classified into six industry weight classes (Classes 3 to 8), and the Energy Commission subdivides Class 8 trucks by vocation. Furthermore, the Energy Commission classifies buses as urban transit buses, shuttle buses, school buses, and motor coaches. Finally, the fuel types requested by the Energy Commission include:

- Gasoline-electric hybrid.
- Diesel-electric hybrid.
- Diesel-hydraulic hybrid.
- Battery-electric.
- Direct or catenary electric.
- Fuel cell electric.
- Ethanol (E85).
- Compressed natural gas.
- Liquefied natural gas.
- Propane.

In general, gasoline and diesel engines are common in smaller (Classes 3 to 5) trucks, while heavier vehicles are typically powered by diesel engines. In the highest weight classes, diesel engines are used in more than 95 percent of all trucks. Hence, the focus of the analysis starts with diesel-powered vehicles, while alternative powertrains are considered relative to diesel.

To generate forecasts of fuel economy, H-D Systems considered several fuel efficiency technologies in this analysis, including:

- Improvements in engine efficiency and reduction of losses in the engine, transmissions, and axles.
- A reduction in vehicle weight, aerodynamic drag, or tire-rolling resistance.

The technologies available and the respective costs and benefits are summarized in this report.

This report provides forecasts for two scenarios. The first is a high electricity demand case that assumes electric vehicles are successful and uses the high-volume production forecast to generate electric vehicle prices. The second is a low electricity demand case that uses the current (low-volume production) prices of electric vehicles and assumes manufacturers are able to achieve cost reductions through increasing manufacturing experience but not of scale for the forecast. This scenario also uses the high transit bus prices from the California Air Resources Board as the starting point for prices in 2017 and assumes benefits of learning but not of scale for the forecast. The forecasts project that for all internal combustion engine-powered vehicles from 2017 to 2030

- Vehicles in Classes 3 and 4 (mostly large pickups and vans) will increase fuel economy by about 25 to 29 percent.
- Medium-duty trucks in Classes 6 and 7 that operate in mixed suburban and urban routes will increase fuel economy by 22 to 25 percent.
- Vehicles in mostly urban use like garbage trucks and urban buses will have improvements in fuel economy of 9 to 12 percent.
- Long-haul trucks in Classes 7 and 8 will see the largest improvement of 29 to 32 percent in fuel economy.

Electrical vehicles in each class will see smaller improvements in fuel efficiency because the electric motor is already very efficient and future gains in efficiency will be small; hence, most of the efficiency improvement is associated with improvements to body technology. Costs of electric vehicles, however, are forecast to decline mostly due to battery cost reduction and improved economies of scale.

CHAPTER 1: Introduction

The California Energy Commission's Transportation Energy Forecasting Unit (TEFU) has a set of transportation energy demand models that require forecasts of medium- and heavy-duty vehicle attributes (fuel economy and price) from 2016 to 2030. The models are used by TEFU to estimate future fuel consumption and the market penetration of alternative fuel vehicles, which help inform the *2017 Integrated Energy Policy Report (IEPR)* and provide analytical support for implementing state policy goals. This report documents the forecast of medium- and heavy-duty vehicle fuel economy and price, and the technological and modeling assumptions used to derive the forecast.

The fuel economy and greenhouse gas (GHG) emissions of medium- and heavy-duty vehicles are required to meet specific mandated levels by the federal *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-duty Engines and Vehicles* for the 2010-to-2017 period. They have recently been extended to the 2018-to-2027 period by the "Phase 2" regulations. The standards require a high level of effort from heavy-duty vehicle manufacturers and essentially make the future fuel economy levels for each vehicle weight class virtually independent of future fuel prices unless prices rise to unanticipated levels. Fuel prices could still affect the mix of vehicle weight classes and fuel types sold, but for a given weight class and fuel type, fuel economy improvements are forced by standards rather than economics.

The way to meet the fuel economy standards is by improving the technology of trucks. A comprehensive analysis of technological improvements has been completed by the United States Environmental Protection Agency (U.S. EPA) and the National Highway Traffic Safety Administration (NHTSA) in support of the 2014-2017 Phase 1 and 2018-2027 Phase 2 regulations. The analysis builds on earlier work on heavy-duty vehicle technology by the U.S. EPA, National Academy of Sciences (NAS), and H-D Systems (HDS). The forecast relies on technologies being added to a known baseline (2017) of vehicle characteristics. The more recent work by U.S. EPA/NHTSA is documented in the Regulatory Impact Assessment (RIA) released in 2016,[1] and this forecast uses many elements of the standards derived in the RIA. Since the standards are technology-forcing,[2] the analysis in the RIA is used extensively with some modification to derive the forecast for the Energy Commission.

Chapter 2 of this report describes the weight classes and fuel types used by the Energy Commission and maps the Commission's vehicle class definitions to those used by the EPA and NHTSA. In addition to the weight class and fuel type classifications, trucks in the same weight classes are used in applications with different use-based duty cycles.

1 U.S. EPA/NHTSA. August 2016. *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Vehicles, Regulatory Impact Assessment, EPA Report 420-R-16-900.*
2 "Technology forcing" refers to regulations that require (force) the use of more technology than demanded by the free market to achieve performance standards.

The Energy Commission's weight class by application is matched to the appropriate duty cycle definitions used in the RIA.

Chapter 3 summarizes the technology analysis in the RIA and provides a listing of the technologies used to improve fuel economy. Based on earlier HDS analysis of medium- and heavy-duty technology for the U.S. Department of Energy (DOE),[3] aspects of the RIA that H-D Systems believes overstate on-road fuel economy potential of some technologies are corrected for in the forecast developed for the Energy Commission, and these corrections are described. HDS' analysis for DOE is provided as an attachment to this report. The Energy Commission's forecast also requires data for battery-electric, fuel cell electric, and direct electric drive vehicles, which are not covered in the RIA, and HDS' assumptions are documented in this section.

Chapter 4 summarizes HDS' forecast, which is similar to the EPA/NHTSA forecast except for the correction to some of the technology benefits employed by EPA and NHTSA. The forecasts in the RIA (from which the HDS forecasts are derived) are shown in this section, and the forecasts developed for the Energy Commission are listed.

The attached supplement (the DOE report) also provides some limited historical data on medium- and heavy-duty truck fuel economy derived from the 2002 Vehicle Inventory and Use Survey (2002 VIUS)[4] and other data sources. VIUS was known as the Truck Inventory and Use Survey, or TIUS, before 1997.

3 EEA/ICF. December 2011. *Technological Potential to Reduce Heavy-Duty Truck Fuel Consumption to 2025*, report to the DOE Office of Policy.
4 Found at www.census.gov/svsd/www/vius/2002.html.

CHAPTER 2: Vehicle Classes Used in Forecast

Weight Classes

The California Energy Commission's transportation energy demand models require medium- and heavy-duty vehicle attributes by vehicle weight class and fuel type. Medium- and heavy-duty trucks are generally classified by industry weight Classes 3 to 8, and the class definitions, as well as the typical vehicle types in each class, are provided below.

Weight Classes 3, 4, and 5 are referred to as *light heavy-duty (LHD) trucks* by the automotive industry and EPA (but as medium-duty by the Energy Commission) and span the 10,000-to-19,000 pound gross vehicle weight (GVW) range. Class 3 consists mostly of pickup trucks and cargo vans, like the Ford F-350 and Dodge D-3500, as well as a few small size "cabover" Japanese trucks. Classes 4 and 5 are increasingly dominated by the Japanese models, although pickup trucks like the Ford F-450 and 550 have significant market share. Vehicle sales in this class are about 70 percent diesel and 30 percent gasoline. Trucks in this class are used for light commercial activity like plumbing, lawn maintenance, and utility support, while the Japanese trucks are used typically for local pickup and delivery.

Weight Classes 6 and 7 are referred to as *medium heavy-duty (MHD) trucks* and span the 19,000-to-33,000 pound GVW range. These classes are dominated by conventional two-axle straight trucks and were almost completely diesel-powered, although Ford reintroduced gasoline-powered models in the last two years in response to high diesel fuel prices. Trucks in this class are used for urban pickup and delivery, as well as suburban and rural freight distribution. A significant fraction of these vehicles are vocational trucks used by local gas and electric utilities and by city services.

Class 8, which is referred to as *heavy heavy-duty (HHD) trucks*, is usually split into two subclasses, 8A and 8B. Trucks in Class 8A are typically three-axle trucks covering the 35,000-to-55,000-pound weight range and include trucks used in construction and waste disposal, as well as suburban and rural freight distribution. Class 8B trucks are four- and five-axle trucks in the 60,000-to-80,000 pound weight range, with the majority of these trucks devoted to medium- (between 100 and 500 miles) and long-haul (greater than 500 miles) freight distribution. Heavy construction trucks, tanker trucks, and specialized vocational trucks have a smaller share of the 8B market. Trucks in Class 8A and 8B are usually diesel-powered.

Motorhomes and buses – including school buses, transit buses, and long-haul coaches – are derived from truck chassis. School buses and small motorhomes are typically Class 5 or 6 (depending on length) and are about 60 percent diesel-powered, with gasoline and alternative fuels like compressed natural gas (CNG) or propane used in many buses. Large motorhomes, transit buses, and motor coaches are in the 30,000-to-35,000-pound

GVW range (that is, Class 7 or 8A) and are usually diesel–powered, although a significant portion of transit buses use compressed (CNG) or liquefied (LNG) natural gas.

The RIA provides an overview of the use type for all vocational vehicles; these data from Table 2-65 of the RIA are shown in Table 2-1. Long-haul Class 8 trucks operate more than 80 percent of total miles on highways. Multipurpose driving involves a mix of city and urban highway driving, while regional driving is on suburban and state highway routes.

Table 2-1: Operating Duty Cycle for Vocational Vehicles

		REGIONAL	MULTIPURPOSE	URBAN
Class 4-5 straight truck		9%	41%	50%
Class 6-7 straight truck		15%	50%	35%
Class 8 straight truck		20%	60%	20%
Long haul Class 6 to 8 straight truck, motorhome		100%	0%	0%
School Bus		0%	10%	90%
Transit Bus		0%	0%	100%
Refuse truck		0%	10%	90%

Source: U.S. EPA/NHSTA RIA. Figures are percentages of VMT.

Alternative Fuels and the Energy Commission's Class/Fuel Matrix

The Energy Commission's Truck Choice model estimates market share by vehicle weight class, vocation, and fuel type. The truck fuel types modeled by the Energy Commission include the:

- Gasoline-electric hybrid.
- Diesel-electric hybrid.
- Diesel-hydraulic hybrid.
- Battery–electric.
- Direct or catenary electric.
- Fuel cell electric.
- Ethanol (E85).
- Compressed natural gas (CNG).
- Liquefied natural gas (LNG).
- Propane.

Not all combinations of fuel types and weight classes are expected to be introduced into the market. Hence, a matrix of expected combinations was agreed upon by H-D Systems and Energy Commission staff, and the combinations are shown in Table 2-2.

Table 2-2: California Energy Commission Vehicle Class and Fuel Type Matrix

#	CEC Vehicle Class	Gasoline	Gasoline Electric Hybrid	Diesel	Diesel Electric Hybrid	Diesel Hydraulic Hybrid	Battery-Electric Vehicles	Direct (Catenary) Electric	Fuel Cell Vehicles	E85 (ethos engine)	Compressed Natural Gas (CNG)*	Liquefied Natural gas (LNG)*	Propane (LPG)
GVWR 3	GVWR 3	O	O	O	P		P			O	A		A
GVWR 4 to 6	GVWR 4	O	O	O	P	A	O			O	A		A
	GVWR 5	O		O		A	O			O	A		
	GVWR 6			O	P	P	O				A		
GVWR 7 & 8	GVWR 7			O	P						A		
	GVWR 8 Single Unit			O							A	A	
GVWR 8	Combination (California)			O				P			A	A	
GVWR 8	Garbage			O	O	A					A	A	
GVWR 8	Combination (Interstate)			O								O	O
Motorhomes	GVWR 3	O		O									
	GVWR 4 to 6	O		O							A		
Bus	Urban Transit			O	O	A	P	O	P		A		
	Motor Coach			O									
	School Bus	O		O			P				A		A
	Shuttle Bus	O				A	O		A		A		

Source: California Energy Commission and H-D Systems

O – Original Equipment Manufacturer P – Pilot Production** A – Aftermarket

* Includes Low NOx engines.

** Pilot production refers to production of less than 100 units per year.

H-D Systems' Observations on Truck Availability by Fuel Type

The low oxides of nitrogen (NO_x) natural gas engine was included in the standard natural gas category as it is a transient product for the 2018-2022 time frame (after 2022, HDS expects all natural gas trucks to have low NO_x natural gas engines).

Gasoline electric hybrids are not offered in Classes 3 to 5 but may be offered in 2019 and later years as full-size pickup manufacturers plan to introduce hybrids in the light-duty versions of these pickups that have similar bodies and drivetrains. Diesel hybrids have also been recently introduced into the market by select Japanese manufacturers in Classes 5 and 6 trucks.

Hydraulic hybrids **do not** appear to be under serious consideration by truck manufacturers but are available as aftermarket conversions by manufacturers such as Bosch-Rexroth and Parker Hannifin. Both series and parallel types are offered, but because of lower costs, HDS has included only the series type in the forecast as an aftermarket product.

Electric vehicles of many types are expected to be introduced into the market. Two Asian manufacturers, BYD and Fuso, are offering battery-electric vehicles in Classes 5, 6, and 7, while there is pilot production of transit and school buses. (*Pilot production* is a term used in this report to refer to production of fewer than 100 units per year.) Electric trucks operating like trolleys with a catenary but also having a battery for short-range unconnected use are also being discussed, with a pilot program underway in the South Coast Air Quality Management District. Fuel cell trucks are not yet available, although there is pilot production of fuel cell buses.

E85 vehicles are available directly from manufacturers of Classes 3, 4, and 5 gasoline-powered trucks and are sold as gasoline- and E85-compatible flex-fuel vehicles. CNG vehicles and propane vehicles in these classes are aftermarket conversions of gasoline vehicles (not diesel engines), as no manufacturer offers alternative fuel vehicles directly, but some like Ford have "qualified" aftermarket suppliers. In 2015, one manufacturer (Cummins-Westport) offered a 6.6 liter diesel engine conversion to CNG suitable for this market, but anecdotal evidence suggests only minor sales in markets for Classes 4 and 5 trucks. Aftermarket gasoline engine conversions to CNG also have modest sales, accounting for less than 1 percent of Classes 3, 4, and 5 sales nationally.

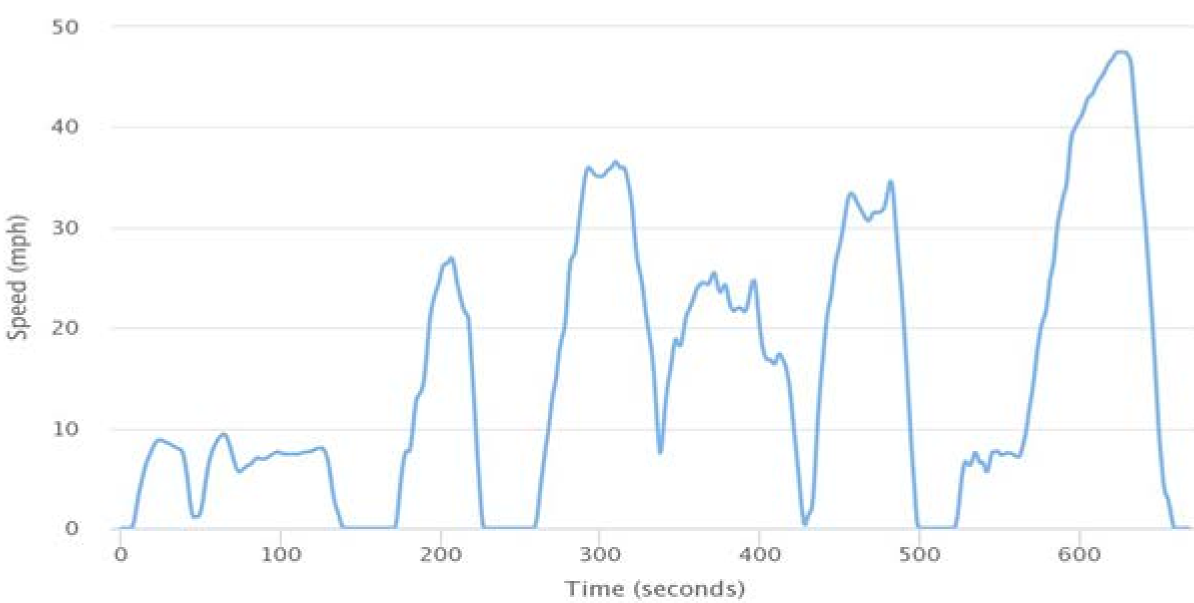
CNG and LNG vehicles in Classes 6, 7, and 8A use specially converted diesel engines, and there is only one supplier for these engines – Cummins-Westport, which provides the 6.6 liter and 9 liter engines. CNG and LNG have found significant market penetration in the urban transit bus market and in garbage trucks, where local or state regulations sometimes require the use of natural gas. Westport introduced a compression ignition natural gas engine for the Class 8B market but withdrew it in 2014 due to poor sales. A new 12 liter Cummins-Westport spark ignition engine suitable for this market was introduced in 2016. All the available diesel engine-based conversions use spark ignitions for CNG and are less energy-efficient than the comparable power diesel engine.

Cross-Classification Matrix

The Energy Commission's weight classifications and vehicle types are not the same as the EPA/NHTSA-based vehicle use type and weight classes, and a mapping between the two classifications is required to translate the regulatory requirements applicable to each Energy Commission class.

The translation is based upon an understanding of the class-specific duty cycles used by EPA for testing the vehicles for compliance. EPA has settled on using three test cycles and two idle tests for assessing compliance, and class-specific figures are determined by different weightings of each cycle used to construct a composite figure. The three test cycles are the 65 mph steady-state cruise, the 55 mph steady-state cruise, and the California Air Resources Board (CARB) transient test. The cruise tests for the 2018-2027 Phase 2 standards involve simulation of road gradients, whereas the same cruise modes for the Phase 1 standards did not have any gradient. The CARB transient test, shown as a speed-time trace in Figure 2-1, represents typical urban driving and includes some higher speed portions in the 40-to-50-mph range that occurs along major arterials and urban highways. The two idle modes are in parked and drive (transmission engaged) modes, respectively. Each truck type class is assigned a mix of the five modes to derive the composite fuel economy and GHG emissions standard.

Figure 2-1: CARB HHDDT Transient Segment



Source: Diesel.net (www.dieselnet.com/standards/cycles/index.php).

The EPA specified duty cycle mix from Tables 3-16 and 3-19 of the RIA, according to the related classification, is shown below. The nonidle modes add to 100 percent.

Table 2-3: EPA Duty Cycle Mix

		Transient	55 mph	65 mph	Idle Drive	Idle-Park
Vocational Regional		20%	24%	56%	0%	25%
Vocational Multipurpose		54%	29%	17%	17%	25%
Vocational Multipurpose (Class 8)		54%	23%	23%	17%	25%
Vocational Urban		92%	8%	0%	15%	25%
Regional Day Cab		19%	17%	64%	NA	NA
Long Haul (Sleeper)		5%	9%	86%	NA	NA

Source: U.S. EPA/NHSTA RIA. Percentages are in terms of VMT, except for idle, which is in percentage of operating time.

Based on these considerations, HDS developed a cross-classification matrix, as shown in Table 2-3, mapping the Energy Commission's medium- and heavy-duty vehicle classes to the EPA truck regulatory categories

Table 2-4: Cross-Classification Matrix

CEC Class	EPA Regulatory Category
GVWR 3	LHD Multipurpose
GVWR 4	LHD Multipurpose
GVWR 5	LHD Multipurpose
GVWR 6	MHD Multipurpose
GVWR 7	MHD Regional
GVWR 8 Single Unit	HHD multipurpose
GVWR8 Combination (California)	Class 8 Mid-roof Day cab
Garbage	Refuse Truck
GVWR8 IRP (Combination)	Class 8 High Roof Sleeper cab
GVWR 3 motorhome	LHD Regional
GVWR 4 to 6 motorhome	Motorhome
GVWR 7 & 8 motorhome	MHD regional
Urban Transit	Transit bus
Motor Coach	Coach bus
School Bus	School bus

Source: H-D Systems.

CHAPTER 3: Technology to Improve Heavy-Duty Vehicle Fuel Economy

Overview

Diesel engines power the majority of heavy-duty vehicles and are used in more than 95 percent of all trucks in the highest weight classes. Hence, the focus of the analysis is on diesel-powered vehicles, with all other alternatives considered relative to diesel. Fuel efficiency technologies can be broadly separated into those that improve the efficiency by which energy in a fuel is converted to motive power, and by those that reduce the power demand to travel a specific distance. Technologies affecting the former are those that improve engine efficiency and reduce losses in the engine, transmission, and axles. Technologies affecting power demand are those that reduce the weight, aerodynamic drag, or tire-rolling resistance. In the case of trucks, some operational factors like limiting cruise speed or preventing extended idle can improve fuel consumption. The technologies available and the related costs and benefits in both categories are summarized below. The analysis is based on the detailed RIA from the U.S. EPA/NHTSA. Electric vehicles change the entire drivetrain but still benefit from power demand reductions. All the data and fuel efficiency estimates cited in this chapter are from the RIA unless specifically stated otherwise.

Diesel Engines

EPA and NHTSA considered available diesel engine technologies that could improve engine fuel efficiency. A detailed description of each technology can be found in H-D Systems' report on truck fuel economy, which was created for the U.S. Department of Energy and is included as an attachment to this report. The technologies considered were

- Combustion system optimization.
- Model-based control.
- Advances to turbocharging systems.
- Engine air handling systems improvement.
- Parasitic and friction loss reduction.
- After-treatment integration.
- Downsizing and downspeeding.

Combustion System Optimization

Combustion system optimization, featuring piston bowl, injector tip, and the number of holes, in conjunction with the advanced fuel injection system, is able to improve engine performance and fuel efficiency. Examples include the combustion development programs conducted by diesel engine manufacturers funded by the U.S. Department of Energy as part of the Super Truck program. The manufacturers found improvement due to combustion alone was 1 to 2 percent. The agencies determined that it is feasible that fuel consumption could be reduced by as much as 1.0 percent in the agencies' certification cycles in the 2027 time frame by using these technologies.

Some technologies such as homogeneous charge compression ignition, premixed charge compression ignition (PCCI), low-temperature combustion, and reactivity-controlled compression ignition technologies were not included in the agencies' feasibility analysis, as they were unlikely to be commercialized by 2027.

Model-Based Control

Another important area of potential improvement is advanced engine control incorporating model-based calibration to reduce losses of control during transient operation, that is, when operating at varying speeds. Improvements in computing power and speed would make it possible to use more sophisticated algorithms that are more predictive than today's controls. Detroit Diesel recently introduced the next-generation model-based control concept, achieving 4 percent thermal efficiency improvement while reducing emissions in transient operations. More recently, this model-based control technology was put into one of the vehicles for final demonstration under DOE's Super Truck program. The model-based concept features a series of real-time optimizers[5] with multiple inputs and outputs. Real-time model control could be in production during the 2017-2027 time frame, thus significantly improving engine fuel economy.

Advances to the Turbocharging System

Many advanced turbocharger technologies are available in the time frame between Model Years 2021 and 2027, and some of them are already in production, such as the mechanical or electric turbo-compound, the higher-efficiency variable-geometry turbine, and the asymmetric turbocharger.

A turbo-compound system extracts energy from the exhaust to provide additional power. Mechanical turbo-compounding includes a power turbine located downstream of the turbine, which, in turn, is connected to the crankshaft to supply additional power. It was first used in heavy-duty production by Detroit Diesel, which claims a 3 to 5 percent fuel consumption reduction due to the system, while Volvo reports a 2 to 4 percent improvement. Results depend on the duty cycle and require significant time at high load to see an improvement in fuel efficiency. Light load-factor vehicles can expect little or no benefit. Electric turbo-compound is another potential technology that can improve

5 Engine control is optimized for the actual operating cycling of the engine as it occurs, which depends on factors such as the age of the engine.

engine brake efficiency. Since the electric power turbine speed is no longer linked to crankshaft speed, this allows more efficient operation of the turbine. Navistar reports on the order of a 1 to 1.6 percent efficiency improvement over mechanical turbo-compound systems. This concept, however, does not work well with lower engine emissions due to lower exhaust gas temperatures.

Two-stage turbocharger technology has been used in production by Navistar and other manufacturers. Ford's newly developed 6.7 liter diesel engine features a twin-compressor turbocharger. Higher boost with a wider range of operations and higher efficiency can enhance engine performance and, thus, fuel economy. It is expected that this type of technology will continue to be improved by better matching with system requirements and developing higher compressor and turbine efficiency.

Engine Air-Handling System

Various high-efficiency air-handling (air and exhaust transport) processes could be produced with efficiently designed flow paths (including those associated with air cleaners, chambers, conduit, mass airflow sensors, and intake manifolds) and by designing such systems for improved thermal control. Improved turbocharging and air handling systems must include higher-efficiency exhaust gas recirculation (EGR) systems and intercoolers that reduce pressure loss while maximizing the ability to thermally control induction air and EGR. Other components that offer opportunities for improved flow efficiency include cylinder heads, ports, and exhaust manifolds to further reduce pumping losses. Manufacturers report a 1.4 percent to 2 percent fuel efficiency improvement through air-handling system development. Navistar predicts almost 4 percent improvement through a combination of variable intake valve closing timing, which may include a partial Miller cycle,[6] as well as turbocharger efficiency and match improvements.

Engine Parasitic and Friction Reduction

Engine parasitic[7] and friction reduction is another key technical area that can be improved in the 2020-to-2027 time frame. Reduced friction in bearings, valve trains, and the piston-to-liner interface can improve efficiency. Friction reduction opportunities in the engine valve train and at the roller/tappet interfaces exist for several production engines. The piston at the skirt/cylinder wall interface, wrist pin, and oil ring/cylinder wall interface offers opportunities for friction reduction. More advanced lubricating oil will be available in the future and will play a key role in reducing friction. Lube oil and water pumps are another area where efficiency improvements are planned.

Manufacturers report 2 to 3 percent reductions in fuel consumption from a combination of improvements to friction and water/oil pump improvements. Water pump improvements include pump efficiency improvement and variable-speed or on/off

6 The *Miller cycle* is a thermodynamic cycle used in a type of internal combustion engine, where fuel is combusted to extract useful mechanical energy. It is a variant of the standard Otto/Diesel cycle that improves performance at partial (or less than maximum) engine load.
7 *Engine parasitic losses* are energy losses due to vehicle accessories such as the oil and water pumps.

controls. Lube pump improvements are primarily achieved using variable displacement pumps and may include efficiency improvement. EPA contractor reports show that if the exact certification cycles, weighting, and vehicle weights are used, the friction reduction in the Phase 2 time frame is in the range of 1.5 percent compared to a 2018 baseline engine.

Integrated Aftertreatment System

All manufacturers now use diesel particulate filters to reduce particulate matter (PM) and selective catalytic reduction (SCR) to reduce NO_x emissions, and these types of aftertreatment technologies are likely to be used for compliance with criteria pollutant standards for many years to come. There are three areas considered to improve integrated aftertreatment systems, which result in a reduction of fuel consumption. The first is better combustion system optimization through increased aftertreatment efficiency. The second is reduced back pressure (the pressure in an exhaust pipe due to restriction of air flow that an engine must work against) through further development of the devices themselves. The third is reduced ammonia slip, or unreacted ammonia, out of SCR during transient operation, thus reducing net urea consumption. Cummins reports a 0.5 percent improvement through improved aftertreatment flow. Detroit Diesel projects a 2 percent fuel efficiency improvement through reduced use of EGR, thinner wall diesel particulate filters, improved SCR cell density, and catalyst material optimization[8].

Engine Downsizing and Downspeeding

Engine downsizing[9] can be more effective if it is combined with downspeeding[10] when total power demand is reduced. This lower power demand shifts the vehicle operating points to lower load zones, which moves the engine operating point to a less efficient area. Downspeeding allows the engine to move back into the optimum operating points, resulting in reduced fuel consumption. Detroit Diesel also shows that engine downsizing can result in friction reduction due to a reduction in engine surface area when compared to a bigger bore engine.

Engine downspeeding can also be an effective fuel efficiency technology even when used alone (that is, not in combination with engine downsizing), especially when a vehicle uses a fast axle ratio. In this situation, downspeeding can allow the engine to operate in a lower speed zone closer to or just in the middle of the optimal efficiency operating point of the engine. On the other hand, from a vehicle operating standard point, the benefit of downspeeding is realized primarily by using a lower axle ratio, allowing the engine to operate in an optimal zone.

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8 Catalyst material optimization is the selection of catalytic material to optimize emissions reductions of particulate matter and NOx.
9 Engine downsizing represents the reduction the engine size with no loss in power.
10 Engine operation at lower RPM to reduction friction losses and operate the engine at a lower fuel consumption point.

Waste Heat Recovery

Organic Rankine cycle waste heat recovery (WHR) systems have been under development for decades, but performance and cost issues have prevented commercialization. The basic approach of a WHR system is to use engine exhaust waste heat from multiple sources to evaporate a working fluid in a heat exchanger. This evaporated fluid is then passed through a turbine or equivalent expander to create mechanical or electrical power. The working fluid is then condensed back to the fluid in the fluid reservoir tank and returned to the flow circuit via a pump to restart the cycle.

With support of the U.S. Department of Energy, three major engine and vehicle manufacturers have developed WHR systems under the Super Truck program.[11] The agencies recognize the many challenges that would need to be overcome but believe with enough time and development effort, this can be done. Manufacturers have stated that the WHR systems in the literature and used in the DOE Super Truck program are still in the research and development stage and are a long way from reaching production. The U.S. EPA and NHTSA have been optimistic and have included WHR systems in their forecast. HDS does not estimate that the WHR will be cost–effective, and EPA's own estimates show that the cost is more than $1,500 per 1 percent improvement in fuel consumption, which is significantly higher than those for other technologies. While the agencies project a 5 percent market penetration in 2024 and 25 percent market penetration in 2027 for WHR, HDS has set it to zero. This constitutes the only major difference in the diesel engine technology forecast from the 2027 forecast in the RIA.

Gasoline Engines

The U.S. EPA and NHTSA did not set aggressive standards for gasoline engines as they believed that the 2016 standard overstated the performance of actual 2016 gasoline engines. Many technologies developed for use with light-duty pickup trucks are also available for the light heavy-duty class. The most prominent technologies are:

- Direct injection with increased compression ratio.
- Engine friction and parasitic loss reduction.
- Variable-cylinder management (or cylinder cut).
- Downsizing and downspeeding.

The number of engine families in the light heavy-duty vehicle segment is relatively few (about six) and are derived mostly from light-duty V8 engines. (Ford has a V10 engine.) As of 2017, all employ port fuel injection and conversion to direct injection, like many of their light-duty counterparts, where a one-unit increase in compression ratio can provide fuel consumption reduction of 2 to 2.5 percent.

11 The Super Truck program is a U.S. DOE program to test advanced truck technology.

Engine friction and parasitic loss reduction uses technologies similar to those described for diesel and offer a 1 to 1.5 percent fuel consumption reduction over the next 10 years. Cylinder-cut technology is widely employed in light-duty V8 engines and some light-heavy V8 models, but the benefit in fuel consumption is smaller than for light-duty vehicles, since the engines are more heavily loaded. The benefit for light-duty engines is about 6 percent, while in the light heavy-duty segment, it falls to about 3 percent.

Downsized turbocharged engines are less likely in the light heavy-duty segment as such engines offer no benefit over naturally aspirated engines at high loads. As a result, HDS agrees with the U.S. EPA/NHTSA position that such engines will have limited penetration in the Classes 3 to 5 vehicle segments. Downsizing and downspeeding are closely related to turbocharging and increasing engine specific power, so that the impact of these technologies will also be limited, except to the extent made possible by transmission changes.

The net benefit of all technological improvements is in the 6 to 7 percent range but some engines feature cylinder cut technology in 2017, and not all engines will receive all technology improvements by 2027, especially in the absence of forcing standards. Hence, we estimate a net average fuel consumption reduction of 4 to 5 percent between 2017 and 2027, which is quite similar to the benefits forecast from diesel engine improvements over the same time frame.

Natural Gas Engines

As noted in Chapter 2, CNG engines for the light heavy-duty segment are usually conversions of gasoline engines in the aftermarket. (The "aftermarket" refers to modifications made to a vehicle after purchase by a third party and not the manufacturer.) These conversions do not change the basic engine calibrations or hardware but add gas injectors to provide a stoichiometric mixture of air-fuel to the engine. The net result is usually no significant change in the energy efficiency of natural gas engines relative to the unconverted gasoline engine, in terms of vehicle energy consumption per mile.

Natural gas engines used in Classes 6, 7, and 8A trucks are conversions of diesel engines to gasoline (or spark ignition) engines. These engines feature turbocharging and have a relatively high compression ratio; so they are more efficient than conventional gasoline engines but still significantly less efficient than comparable diesel engines. The engines operate at a stoichiometric air-fuel ratio that allows the use of a cheaper emission control system to meet standards relative to the complex system used in a diesel engine. The RIA suggests that these engines are about 15 percent less fuel-efficient than a diesel engine over the same duty cycle.

While the only natural gas engine available for Class 8B trucks today is also a spark ignition engine, there have been examples of natural gas engines in limited production that more closely resemble diesel-cycle engines and use a small amount of diesel fuel for a pilot injection to initiate combustion. However, the emission control system is as expensive as the one used for diesel engines, and the two fuel systems result in higher engine costs and complexity. Fuel efficiency is expected to be only 3 to 5 percent worse than a comparable diesel engine, according to the RIA. Such engines could be introduced into the market in 2018 or 2019.

Transmissions and Axles

Transmissions and axles are part of the drivetrain, and ways to improve transmissions include electronic controls, shift strategy, gear efficiency, and gear ratios. The relative importance of having an efficient transmission increases when vehicles operate in conditions with a higher shift density. Each shift represents an opportunity to lose speed or power that would have to be regained after the shift is completed. Further, each shift engages gears that have inherent inefficiencies. Optimization of the vehicle gearing to engine performance through selection of transmission gear ratios, final drive gear ratios, and tire size can play a significant role in reducing fuel consumption and GHGs. Optimization of gear selection versus vehicle and engine speed accomplished through driver training or automated transmission gear selection can provide additional reductions.

Manufacturers of light and medium heavy-duty vehicles can replace six-speed transmissions with eight-speed or more automatic transmissions. Additional ratios allow for optimizing engine operation over a wider range of conditions, but this is subject to diminishing returns as the number of speeds increases. Also, the additional shifting of such a transmission can be perceived as bothersome to some consumers, so manufacturers need to develop strategies for smooth shifts. The RIA rulemaking projected that eight-speed transmissions could incrementally reduce fuel consumption by 2 to 3 percent from a baseline six-speed automatic transmission over some test cycles. The efficiency of gears can be improved by reducing friction and minimizing mechanical losses. During operation, the controller of an automatic transmission manages the transmission by scheduling the upshift or downshift, and locking or allowing the torque converter to slip based on a preprogrammed shift schedule. This aggressive shift logic[12] can be employed to maximize fuel efficiency by modifying the shift schedule[13] to upshift earlier and inhibit downshifts under some conditions, allowing the engine to operate at higher efficiency points.

The manual transmission has traditionally been more efficient than automatic transmissions, and advances in electronics and computer processing power allow for more efficiency from a manual transmission architecture with fully automated shifting. The two primary manual transmission architectures employing automated shifting are the automated manual transmission (AMT) and the dual-clutch transmission. When implemented well, these more mechanically efficient designs provide better fuel efficiency than conventional automatic transmission designs and, potentially, even fully

12 *Aggressive shift logic* refers to maximizing fuel economy by forecasting when transmission shift changes may be needed.
13 The shift schedule refers to when a transmission shift change is scheduled to occur.

manual transmissions. An AMT is mechanically similar to a conventional manual transmission, but shifting and launch functions are automatically controlled by electronics. The term *AMT* generally refers to a single-clutch design (differentiating it from a dual-clutch transmission), which is essentially a manual transmission with automated clutch and shifting. Because of shift quality issues with single-clutch designs, dual-clutch designs are more common in light-duty applications, where driver acceptance is of primary importance. For heavy-duty vehicles, shift quality remains important but is less so when compared to light-duty vehicles. As a result, the single-clutch AMT can be an attractive technology for heavy-duty vehicles and provides up to 2 percent fuel consumption reduction.

Axle efficiency is improved by reducing two categories of losses: mechanical losses (due to friction) and spin losses (due to energy transfer to unwanted axle fluid churning or spin). Mechanical losses can be reduced by reducing the friction between the two gears in contact. Frictional losses are proportional to the torque on the axle but are not a function of rotational speed of the axle. Spin losses, on the other hand, are a function of speed, not torque. One of the main ways to reduce the spin losses of the axle is by using a lower-viscosity lubricant. Some high-performance, lower-viscosity oil formulations have been designed to have superior performance at high operating temperatures and may have extended change intervals. Axle efficiency improvements can contribute up to 2 percent improvement in fuel consumption. In dual-rear-axle vehicles, using only one axle for traction power reduces losses but can be traction limited under slippery conditions. An axle-disconnect system allows the rear axle to be engaged as required and provides a 1.5 percent gain in fuel economy.

Aerodynamics

Up to 25 percent of the fuel consumed by a line-haul tractor traveling at highway speeds is used to overcome aerodynamic drag forces, making aerodynamic drag a significant contributor to the GHG emissions and fuel consumption of a Class 7 or 8 tractor. Because aerodynamic drag varies by the square of the vehicle speed, small changes in the tractor aerodynamics can have significant impacts on GHG emissions and fuel efficiency of that vehicle. With much of the driving at highway speed, the benefits of reduced aerodynamic drag for Class 7 or 8 tractors can be significant, but for vehicles that operate primarily in urban areas and at low speed, aerodynamics are not a significant factor in fuel consumption. The common measure of aerodynamic efficiency is the coefficient of drag (C_d). The aerodynamic drag force (the force the vehicle must overcome due to air) is a function of C_d, the area presented to the wind (the projected area perpendicular to the direction of travel or frontal area) known as the drag area, and the square of the vehicle speed. C_d values for today's line-haul fleet typically range from greater than 0.80 for a classic body tractor to about 0.58 for tractors that incorporate a full package of widely commercially available aerodynamic features on both the tractor and trailer.

Aerodynamic drag reduction is accompanied by smoothing the shape of the vehicle to make it more aerodynamically efficient, redirecting air to prevent entry into areas of high drag (for example, wheel wells), maintaining smooth air flow in certain areas of the vehicle, or a combination of these. Improving the vehicle shape may include revising the fore components of the vehicle such as rearward canting/raking or smoothing/rounding the edges of the front-end components (for example, bumper, headlights, windshield, hood, cab, mirrors) or integrating the components at key interfaces (for example, windshield/glass to sheet metal) to alleviate vehicle drag. Finally, redirecting the air to prevent low-pressure areas and eliminating areas where turbulent vortices are created reduce drag. Techniques such as blocking gaps in the sheet metal, ducting of components, shaping or extending sheet metal to reduce flow separation and turbulence are methods being considered to direct air from areas of high drag (for example, the underbody, tractor-trailer gap, underbody, or rear of trailer, or a combination of these).

The heavy-duty transport industry implemented significant aerodynamic refinements, but improvements were integrated mostly into tractor bodies with no trailer contribution. Most of the future aerodynamic improvement potential will come from further refinement of the gap between tractor and trailer, underbodies, and the trailer itself, and, to a much lesser extent, improvements in tractor aerodynamics. Operators traditionally resisted aerodynamic trailer add-on technology because of cooling problems, ground clearance, durability, and length limitations imposed on highway trucks. The use of devices such as inflatable adjustable gap seals or retractable skirts (or active devices) should reduce incompatibility issues but will be more difficult to justify for add-on costs and reliability. The institutional trailer issues have been addressed in the Phase 2 rulemaking for 2017 to 2027 to force the aerodynamic devices for trailers to be actually implemented widely in the market.

The U.S. EPA/NHTSA rulemaking for Phase 1 standards had very similar data and identified aerodynamic “packages” which were labeled as Bin 1 to Bin 10. Each bin represents a combination of discrete technologies. Bin 1 is the baseline package with a C_d of 0.79, consistent with HDS data for the “classic” tractor-trailer. EPA has defined Bins 2, 3, and 4 packages in terms of values of 0.72, 0.63, and 0.56, respectively, for C_d. The technologies are generally defined but not specific, as manufacturers have to evaluate the actual aerodynamic performance to compute the C_d *x* A parameter that must fall within predefined values. EPA had also defined a Bin 5 with a C_d value of 0.51 for unspecified future improvements. In its Phase 2 rulemaking, EPA shifted the scale to C_d *x* A units and specified levels for Bins 1 to 6 that are specific to each tractor type, but generally follow the same principles invoked in the 2017 rulemaking.

The aerodynamic simulations for the RIA rely on the two constant speed cycles at 55 mph and 65 mph, respectively. HDS believes that the results overstate the importance of aerodynamics for two reasons. First, most highways with significant freight traffic in California are congested with frequent slowdowns. Even if the average speed is 55 mph or 65 mph, the speedup and slowdown cycles increase energy use, and the fraction of energy lost to aerodynamic drag becomes smaller. Second, the drag values are based on a truck moving in an empty track and does not account for the other vehicles ahead of it that reduce the drag due to the wake effect. Informal platooning of trucks is common on highways as truckers try to capture this aerodynamic benefit at no cost. Data cited in the DOE report in Appendix B suggest that at highway speeds, each 10 percent drag reduction results in a fuel consumption improvement of 3.8 percent rather than 5.2 percent in EPA simulations. Hence, one change made to the U.S. EPA/NHTSA forecast is the reduction of benefits from aerodynamic devices by 27 percent (in other words, 27% = 100% - 3.8%/5.2%). This change affects the fuel economy of regional and long-haul use trucks only.

Improved Rolling Resistance

Research indicates that the contribution of a tire to overall vehicle fuel efficiency is roughly proportional to the vehicle weight. Energy loss associated with tires is mainly due to deformation of the tires under the load of the vehicle, known as *hysteresis*, but smaller losses result from aerodynamic drag, and other friction forces between the tire and road surface and the tire and wheel rim. Collectively, the forces that result in energy loss from the tires are referred to as *rolling resistance*. Rolling resistance is a factor considered in the design of the tire and is affected by the tread and casing compound materials, the architecture of the casing, tread design, and the tire manufacturing process. It is estimated that 35 to 50 percent of the rolling resistance of a tire is from the tread, and the other 50 to 65 percent is from the casing. In addition to the effect on fuel consumption, design and use characteristics of tires also influence durability, traction, vehicle handling, ride comfort, and noise. Tires that have higher rolling resistance likely represent a different trade-off with one or more of these other tire attributes. Tire inflation can also affect rolling resistance in that under-inflated tires can result in increased deformation and contact with the road surface.

According to an energy audit cited in the RIA, tires were shown to be the second largest contributor to energy losses for a Class 6 delivery truck at 50 percent load and speeds up to 35 mph (a typical average speed of urban delivery vehicles). For Class 8 tractor-trailers, the share of vehicle energy required to overcome rolling resistance is estimated at nearly 23 percent. On a cycle basis, the energy use attributed to tires varies from 20 to 35 percent, depending on weight class and duty cycle.

Differences in rolling resistance of up to 50 percent have been identified for tires designed to equip the same vehicle. Low-rolling-resistance tires are commercially available from most tire manufacturers and can be applied to vehicles in all medium- and heavy-duty vehicle classes. Low-rolling-resistance tires can be offered for dual-assembly tires and as wide-base singles.

Wide-base singles (WBS) are intended primarily for combination tractor-trailers, but some vocational vehicles are able to accommodate them. In the early years of this technology, some states and local governments restricted use of WBS, but many of these restrictions have since been lifted. A *wide-base single* is a larger tire with a lower profile that replaces two standard tires. Generally, a wide-base single tire has less sidewall flexing compared to a dual assembly; therefore, less hysteresis occurs. Compared to a dual-tire assembly, wide-base singles also produce less aerodynamic resistance or drag. Wide-base singles can contribute to improving the fuel efficiency of a vehicle through design as a low-rolling-resistance tire or through vehicle weight reduction or both. The use of fuel-efficient wide-base singles can reduce rolling resistance by 3.7 to 4.9 percent compared to the most equivalent dual tire. The data collected based on field testing indicate that tractors equipped with wide-base singles on the drive axle experience better fuel efficiency than tractors equipped with dual tires, independent of the type of tire on the trailer. This field study in particular indicated a 6.2 percent improvement in fuel efficiency from wide-base singles. There are also weight savings associated with wide-base singles compared to dual tires. Wide-base singles can reduce the weight of a tractor and trailer by as much as 1,000 pounds when combined with aluminum wheels.

Tire Inflation Monitoring and Maintenance Systems

Proper tire inflation is critical to maintaining proper stress distribution in the tire, which reduces heat loss and rolling resistance. Tires with reduced inflation pressure exhibit more sidewall flexing and tread shearing, resulting in greater rolling resistance than a tire operating at its optimal inflation pressure. Tractor-trailers operating with all tires underinflated by 10 psi have been shown to increase fuel consumed by up to one percent. Tires can gradually lose pressure from small punctures, leaky valves, or simply diffusion through the tire casing. Changes in ambient temperature can also affect tire pressure. Trailers that remain unused for long periods between hauls may experience any of these conditions. To achieve the intended fuel efficiency benefits of low-rolling-resistance tires, it is critical that tires are maintained at the proper inflation pressure. Tire pressure monitoring (TPM) and automatic tire inflation (ATI) systems are designed to address underinflated tires. Both systems alert drivers if tire pressure drops below the set point. TPM systems monitor the tires and require user-interaction to reinflate to the appropriate pressure. Unless the vehicle experiences a catastrophic tire failure, simply alerting the driver that the tire pressure is low may not necessarily result in reinflation as the driver may continue driving to the destination before addressing the tires. Current ATI systems take advantage of air brake systems of trailers to supply air back into the tires (continuously or on demand) until a selected pressure is achieved. In the event of a slow leak, ATI systems have the added benefit of maintaining enough pressure to allow the driver to get to a safe stopping area. The RIA estimates the fuel consumption reduction due to TPM and ATI systems to be 1 and 1.2 percent, respectively.

Weight Reduction

Weight reduction is a technology that can be used in a manufacturer's strategy to meet the Phase 2 standards. Vehicle weight reduction (also referred to as "light-weighting") decreases fuel consumption by reducing the energy demand needed to overcome inertia forces and rolling resistance. Reduced weight in heavy-duty vehicles can benefit fuel efficiency and reduce carbon dioxide (CO_2) emissions in two ways. If a truck is running at the gross vehicle weight limit with high-density freight, more freight can be carried on each trip, increasing the payload efficiency of the truck in ton-miles per gallon. If the vehicle is carrying lower density freight and is below the GVWR (or gross combination weight of the tractor and trailer) limit, the total vehicle mass is decreased, reducing rolling resistance and the power required to accelerate or climb grades.

Although many gains have been made to reduce vehicle mass, many of the new features being added to modern tractors to benefit fuel efficiency, such as additional aerodynamic features or idle reduction systems, increase vehicle mass, causing the total mass to stay relatively constant. Hybrid powertrains, fuel cells, and auxiliary power would not only present complex packaging and weight issues; they would increase the need for reductions in the weight of the body, chassis, and powertrain components to maintain vehicle functionality.

Substitution of a material used in an assembly or a component for one with lower density or higher strength or both includes replacing a common material such as mild steel with higher-strength and advanced steel, aluminum, magnesium, and composite materials. It is the typical method to reduce weight. In practice, material substitution tends to be specific to the manufacturer and situation. The agencies recognized that like any type of mass reduction, material substitution has to be conducted not only with consideration to maintaining equivalent component strength, but to maintaining all the other attributes of that component, system, or vehicle, such as crashworthiness, durability, noise, vibration, and harshness. The principal barriers to overcome in reducing the weight of heavy vehicles are associated with:

- The cost of lightweight materials.
- The difficulties in forming and manufacturing lightweight materials and structures.
- The cost of tooling for use in the manufacture of relatively low-volume vehicles (when compared to automotive production volumes).
- The extreme durability requirements of heavy vehicles.

Moreover, because of the limited production volumes and the high levels of customization in the heavy-duty market, tooling and manufacturing technologies that are used by the light-duty automotive industry are often uneconomical for heavy vehicle manufacturers.

As a result, weight reduction is a relatively costly technology, at about $3 to $10 per pound for a 200-pound package estimated by the U.S. EPA. Even so, for vehicles in service classes where dense, heavy loads are frequently carried, weight reduction can translate directly to additional payload. The agencies project that only modest weight reduction is feasible for all vocational vehicles. The U.S. EPA and NHTSA are predicating the final standards on relatively minor weight reduction comparable to what can be achieved by using aluminum wheels. This package is estimated at 150 pounds for LHD and MHD vehicles and 250 pounds for HHD vehicles, based on 6 and 10 wheels, respectively. The RIA projects an adoption rate of 10 percent, in MY 2021, 30 percent in MY 2024, and 50 percent in MY 2027. The agencies project that manufacturers will have sufficient options of other components eligible for material substitution so that this level of weight reduction will be feasible, even where aluminum wheels are not selected by customers.

Hybrid Drivetrains

Hybridization of the truck drivetrain is, in principle, similar to the hybridization of passenger cars, and many of the same design types are under consideration: series, parallel, and two-mode.[14] One interesting addition to the available hybridization technologies is the hydraulic hybrid, which stores power in the form of a compressed fluid rather than in a battery. However, the series hybrid appears too expensive and heavy for most truck applications. (It may be suitable for buses.) The two-mode hybrid may also be too complex and expensive for most truck applications except those in Class 3, and the manufacturers appear to be considering only the parallel single-motor hybrid for most applications and the hydraulic hybrid for selected applications. Details below are from the report in the attached supplement.

The most popular parallel hybrid configuration is similar in the European Union and the United States. The parallel hybrid uses an electric motor sandwiched between the engine and transmission, with either a single clutch (between motor and transmission) or two clutches (also between engine and transmission). The single-clutch system is more dominant, since motor sizes do not permit pure electric drive. Physically, this system closely resembles the Honda Integrated Motor Assist hybrid system used in passenger cars, although the motor size and battery are three to four times larger for truck application. Typically, motor sizes are in the 50 ± 10 kW (peak) range, and the vast majority of systems have been used on medium-duty Classes 5, 6, and 7 vehicles operating on city cycles ranging in speed from 4 to 20 mph. The Eaton system used by Kenworth and Navistar on their vehicles has a motor rated at 44 kW peak and a battery with energy storage capacity of 1.8 kilowatt-hours (kWh), as an example. The system is mated to a six-speed AMT. ZF, a German transmission manufacturer, has a very similar design with the motor rated at 60 kW. The current system strategy is to provide launch and acceleration assist to the engine and recover braking energy, but the systems do not provide engine idle shutoff and do not downsize the engine to preserve full-load continuous operating performance.

Most of the available data for trucks come from on-road testing in the United States on the Eaton system, and the following results have been reported:

14 In a series hybrid, all motive power is provided by the electric motor. In a parallel hybrid, the gasoline engine and electric motor, either separately or together, can provide motive power, depending on the engine operating mode.

- Hybrid Class 4 vans operating in city pickup and delivery service for UPS showed an average fuel economy improvement of 29 percent for a cycle speed of about 20 mph.
- Hybrid Class 6 trucks tested by Navistar on the dynamometer over the city cycle showed a benefit of 24 percent in fuel economy and about 20 percent on road cycles in California, with speeds in the 20-to-30 mph range.
- Hybrid Class 6 trucks tested in New York over duty cycles with an average speed of about 5 mph showed a fuel economy benefit of 40 percent.

In general, hybrid benefits increase with decreasing speeds and increased number of stop-and–go cycles. The UPS van was an AMT hybrid, while vans tested in California were equipped with automatic transmissions. Since the AMT is about 8 percent more efficient than a conventional automatic, the hybridization benefit for the UPS van was in the low 20 percent range, consistent with Navistar data from California.

Although there has not been any detailed testing of Class 8 hybrids in the United States operating on long-haul routes, Volvo testing in Europe has shown that typical long-haul operation (potentially similar to the long-haul cycle discussed in Chapter 2) has enough acceleration and braking events to provide a 3 to 4 percent improvement in this application with a 25 kW motor. Simulations by the Southwest Research Institute (SwRI) with a 55 kW motor showed a hybrid benefit of 5.7 percent in fuel economy, although the cycle specifics were not provided. Volvo also claimed that hybridization made accessory electrification easier, so that it was able to attain 5 to 6 percent fuel economy benefit in European testing even with the smaller motor size. Accessory electrification is possible in all vehicles but much easier in hybrids, where large amounts of electric power are available. The A/C compressor and power steering are two options with small but significant fuel savings possible.

Current hybrid systems with a 50 kW motor and about 2 kWh of energy storage add about $40,000 to $50,000 to the price, but this is at very low annual sales volumes (probably fewer than 100 units per year) indicative of pilot production. Manufacturers are contemplating using essentially the same system across a wide range of truck weights and applications, with different benefits. Near-term (2014-2015) target prices assuming volumes of about 5,000 to 10,000 per year are in the $20,000 range, and it appears possible that an additional 25 to 35 percent reduction in costs could occur from 2017 levels by 2025 if expected battery and motor price reductions occur from both scale economies and technology evolution. Plug-in hybrids are also being contemplated, although a 40-mile range would require a battery of 50 kWh or more for a medium-duty Class 6 truck with attendant very high costs.

Hydraulic hybrids can absorb high power spikes due to the mechanical nature of energy storage, but total energy storage capacity is limited. In addition, the system is bulky, and space and weight requirements for the hydraulic tanks limit applicability. Truck manufacturers believed that hydraulic hybrids are well suited for some applications with extreme stop-and-go cycles like garbage trucks and urban transit buses. At the same time, they did not believe that these market niches could support adequate sales volume to attain scale and scope economies, unlike an electrical hybrid powertrain, suggesting that markets for such hybrids would not develop to commercial scale.

Electric Vehicles

All-electric vehicles in the truck sector can be of three types. The battery-electric vehicle is widely recognized for cars, and it has been recently introduced in light-heavy and medium-heavy trucks that typically offer 70-to150-mile range and may be suitable for urban pickup and delivery. The fuel cell electric vehicle has been researched for many decades, and some examples have been developed for pilot production, especially for transit buses. Catenary trucks rely on direct attachment to the power grid by means of an overhead wire and a catenary on the truck, like a trolley, but also have some battery storage to allow off-catenary operation for 10 to 20 miles. Some prototypes have been displayed, and a pilot demonstration program is underway in the South Coast air basin.

Battery-electric vehicle characteristics for the base year were developed from actual products offered by Build Your Dreams Auto (BYD). For example, the company offers a Class 5 truck with 155-mile range at 50 percent payload, when using a 145 kWh battery. If the range is associated with 85 percent of battery capacity (as batteries are not discharged below 10 percent of capacity to avoid damage), the actual on-road energy consumption is 0.79 kWh per mile or 1.25 miles/kWh. Since this is at light loading and manufacturers cite the most favorable conditions in advertising, the miles per kWh were derated by 20 percent to derive a fuel efficiency of 1.05 miles per kWh. The consumption for other weight classes was derived either by scaling this figure or by using BYD advertised data. Battery-electric vehicles in a given GVW class have much lower payload than equivalent diesel-powered vehicles due to the current high battery weight of about 7 to 8 kg/kWh.

Estimates for other electric vehicle types were based on a recent paper by researchers at the University of California, Davis[15] (UC Davis) that contrasted the costs and benefits of the three electric truck types outlined above. However, HDS corrected some assumptions in the paper used to calculate energy efficiency and costs. The calculation of energy efficiency was based on steady-state energy consumption on a flat road with zero wind. Transient operation (acceleration and braking), road gradients, and wind result in on-road energy consumption being much higher than the value computed in the paper. The paper also examined a 56,000-pound truck instead of the more typical weight of 66,000 pounds for a 70 percent loaded truck with an 80,000 pound rating and a 33,000 pound empty weight. These corrections increase the estimated electric consumption to 3.57 kwh/mile for a Class 8 electric truck, which is 40 percent higher than the estimate in the UC Davis paper. Estimates for the fuel cell truck energy consumption were similarly adjusted but included another adjustment for the high fuel cell efficiency used in the UC Davis paper. Fuel cells have a peak efficiency point around

15 Zhao, H., et. al. May 2017 (draft). *Zero-Emission Highway Trucking Technologies*. UC Davis Institute of Transportation Studies.

70 percent efficiency at relatively light loads of 20 percent of maximum power, however efficiency declines to about 50 percent at full power. Trucks operate at high loads of 60 percent of maximum power at highway speed (using the estimate of 180 kW at 65 mph), and efficiencies are about 60 percent rather than 65 percent assumed in the UC Davis paper. The energy consumption of all electric trucks will decline with improvements in aerodynamics, rolling resistance, and weight reduction, and the benefits from these technologies was set equal to those for diesel trucks.

Costs for the catenary electric and fuel cell truck were also modified from those in the UC Davis paper. The UC Davis study used costs of electric motors and controllers from studies of light-duty vehicle costs. However, light-duty vehicle motors are rated based on short-term peak power (30 second rating), while heavy-duty trucks must operate continuously at or near peak power. Thus light-duty vehicle motor ratings inflate continuous power ratings by 60 to 80 percent so that a motor rated at 100 kW continuous power for heavy-duty vehicles could be rated at 160 to 180 kW of peak power for light-duty vehicles. In addition, high continuous power ratings of 200 kW or more require a motor cooling system to reject the high heat developed, making the truck motor twice as expensive as a light-duty motor with a similar numerical power rating. Costs of fuel cells also used DOE "target values" for costs, although current costs are an order of magnitude higher. Fuel cells for light-duty vehicles are also not rated for continuous power operation and would need significant upgrades in cooling and durability to operate at high continuous power. H-D Systems' cost estimates for the catenary and fuel cell truck compared to diesel truck are shown below.

The diesel truck is a day cab, 80,000 lb. GVW tractor trailer with a 425 HP engine, while the electric vehicles are equipped with a 300 kW continuous power electric motor. For example, the battery for the catenary vehicle is sized at 75 kWh to provide about a 20-mile range off-grid, while the battery for the fuel cell vehicle is half that size. Costs for the fuel cell are estimated at $200/kW continuous, which is optimistic since current costs are about $500/kW for a light-duty fuel cell, based on the cost of current light-duty fuel cell vehicles. Costs of hydrogen tanks are based on Davis estimates of $500/kg of hydrogen stored, which appears optimistic as current costs are $2,500/kg. The costs based on these assumptions are shown in Table 3-1.

Table 3-1: Cost Estimates for a Class 8 Diesel, Catenary, Electric and Fuel Cell Truck in Volume Production in 2020

Component	Diesel	Catenary	Fuel cell (optimistic)
Glider	50,000	50,000	50,000
Engine or Motor/Controller	20,000	13,000	13,000
Emission Control or Battery	12,000	26,250	13,000
Transmission	6,750	2,000	2,000
Catenary/Fuel Cell	-	7,000	60,000
Hydrogen Tanks	-	-	36,000
Retail Price/Cost Markup	53,250	53,750	83,000
Total	**142,000**	**152,000**	**227,000**

Source: H-D Systems. Assumptions: 300 kW engine, 75kWh battery for catenary, 37 kWh battery for fuel cell

The costs listed above are 2020 direct manufacturing costs (assuming high-volume production of greater than 5,000 units per year globally), while the retail price equivalent is based on a 55 to 60 percent markup. Costs of batteries and motors decline over the forecast period, but costs of other improvements to aerodynamics, tires, weight, and accessories are added to the costs above. The cost data for motors and batteries are based on the CARB technology assessment of battery-electric trucks and buses published in 2015.[16] Truck battery costs, in particular, are expected to decline from $350/kWh (wholesale) in 2020 to $200/kWh in 2030. Motor and controller costs are estimated at $40/kW plus $1,000 in fixed costs, so the cost of a 200 kW (continuous rating) motor and controller is $12,000. This cost is expected to decline to $9,000 by 2030.

Summary

The available technological options are summarized in Table 3-2, the Vehicle Technologies Worksheet. Because technology costs for body-related technologies vary by weight class, the worksheet provides ranges or averages for costs and benefits for several technologies. The RIA provides significant additional detail on costs and benefits, and those can be accessed easily. As noted, benefits for aerodynamics have been reduced relative to the RIA for regional and long-haul trucks to better reflect on-road conditions, but the RIA information is used for all other technologies. Electric vehicles are not included in the RIA forecast, and costs and benefits are from the analysis shown above.

16 California Air Resources Board. October 2015. *Technology Assessment: Medium and Heavy-Duty Battery Electric Trucks and Buses.*

In addition to the technologies in the worksheet, the RIA examined some operational features that include:

- Speed limiters that control maximum speed to 65 mph.
- Adaptive cruise control that permits a look ahead of terrain.
- Extended idle shutoff.
- APU or external power for providing HVAC to sleeper cabs.

All these features have been available for several years in the market, and the benefits of these features through 2030 depend on the extent of use in the base year. Extended idle shutoff is already required in California, and APU/external power for sleeper cabs has been required since 2008 and is included in the baseline. Speed limit enforcement for heavy trucks is also more stringent in California, but the main truck routes are already speed limited by heavy traffic. Hence, these factors may have only small benefits in California and are not considered in this analysis.

Table 3-2: Vehicle Technologies (Costs in 2027)

Technology	Fuel Consumption Benefit %	Cost, 2017$	Comment
Diesel Engines			
Air Handling Improvements	1.1	195	Intake and Turbo Improvement
Combustion/Control	1.1	23	
Friction/Parasitic Loss	1.4	170	
Aftertreatment Improvement	0.6	15	
Downsize/Downspeed	0.4	-126	Cheaper smaller engine
Transient Control	2.0	101	Vocational Trucks only
Turbo-Compound	1.8	890	Regional/Long-haul
CNG Diesel SI Conversion (Class 6/7/8A)	-15 (BTU basis)	35,000	Includes CNG fuel system, tanks, after market installation
CNG Diesel Pilot Injection Conversion (Class 8B)	-4 (BTU basis)	75,000	Includes CNG fuel system, tanks, aftermarket installation
Gasoline Engines			
Direct Injection/Higher CR	2.5	418	Used in light-duty
Friction/ Parasitic Loss	1.2	244	
Cylinder Cutout	3.5	182	Used in some HDT engines
CNG Conversion	0	12,000 to 15,000	Includes CNG fuel system, tanks, aftermarket installation
High-Efficiency Gearbox	1	267	Both manual and automatic
Improved Axle Efficiency	2	116/174	Costs for MDT/HHDT
Tag Axle	1.2	116	For dual-rear-axle trucks
AMT	2	3,850	Relative to manual trans.

Technology	Fuel Consumption Benefit %	Cost, 2017$	Comment
Strong Hybrid	25	6,400	Classes 3,4 only, mixed use
Mild Hybrid	20	13,500	Classes 6/7/8A urban use
10% Drag Reduction	3.8	1,600 for Bin 4	Regional/Long-range trucks
10% Drag Reduction	1.6	170	Mixed-use trucks
10% RRC Reduction	2.9	25 per tire	Regional/Long-range trucks
Weight Reduction 200 Pounds.	0.8	587	LHD/MHD mixed-use
High-Efficiency Alternator	1.0	697 MHD to 1,393 HHD	Vocational trucks only
Electric Power Steering	1.0/0.5		MHD/HHD
Electric A/C Compressor	1.0/0.5		MHD/HHD

Source: H-D Systems.

CHAPTER 4: Forecast of Heavy-Duty Vehicle Attributes

U.S. EPA/NHTSA Standards

As noted in the introduction, the new federal fuel economy standards for medium- and heavy-duty trucks are so stringent that fuel economy to 2030 will be governed by the standards and not by fuel prices (as projected by the Energy Commission) or other economic factors. Two changes have been made to the standards in the RIA to better reflect on-road conditions. First, HDS has assumed that waste heat recovery technology will not be used, which reduces the fuel economy forecast for regional and long-haul Class 8 trucks by 0.7 percent and costs by $1,210. Second, the benefits of aerodynamic drag reduction devices have been reduced by the ratio of 0.38/0.48 or 0.792 to account for the non-steady-state operation[17] on most highways, as well as interference wake drag.[18] Both changes affect only the Classes 7 and 8 regional and long-haul duty cycle segments.

The forecasts for 2021, 2024, and 2027 are shown in the RIA and are reproduced in the following pages. The RIA lists the fuel economy standards at the class level in ton-miles per gallon, with the conversion based on payload in short tons.[19] The conversion back to miles per gallon is relatively simple, since the RIA analysis assumes constant payload by weight class as follows:

- Class 8 tractor trailer: 38,000 pounds
- Class 7 tractor trailer: 25,000 pounds
- Class 8 vocational: 15,000 pounds
- Classes 6/7 vocational: 11,200 pounds
- Classes 3/4/5 vocational: 5,700 pounds

Assumed payloads for special categories (custom chassis) like coaches, transit buses, and others are identical to the above values, depending only on the GVW category these vehicles fall into. The mapping of the EPA classes to Energy Commission medium- and heavy-duty vehicle classes can be found in Chapter 2 of this report. Results for intermediate years were interpolated from the 2017, 2021, 2024, and 2027 values.

17 *Non-steady-state operation* refers to an operation of vehicle with stops and starts.
18 *Interference wake drag* refers to a term from fluid dynamics and represents drag increases or reductions from the wake of the vehicles ahead of a particular vehicle.
19 A *short ton* is equal to 2,000 pounds.

Table 4-1: RIA Estimates for 2021 Fuel Economy by Class (Reproduced From RIA)

REGULATORY SUBCATEGORY	CO_2 GRAMS PER TON-MILE	FUEL CONSUMPTION GALLON PER 1,000 TON-MILE	AVERAGE INCREMENTAL COST PER VEHICLE RELATIVE TO PHASE 1 COSTS IN MODEL YEAR 2021 [A]	AVERAGE PERCENT FUEL CONSUMPTION AND CO_2 IMPROVEMENT IN MY 2021 RELATIVE TO MY 2017
Tractors				
Class 7 Low Roof Day Cab	105.5	10.36346	$5,134	11%
Class 7 Mid Roof Day Cab	113.2	11.11984	$5,134	11%
Class 7 High Roof Day Cab	113.5	11.14931	$5,240	12%
Class 8 Low Roof Day Cab	80.5	7.90766	$5,228	12%
Class 8 Mid Roof Day Cab	85.4	8.38900	$5,228	12%
Class 8 High Roof Day Cab	85.6	8.40864	$5,317	13%
Class 8 Low Roof Sleeper Cab	72.3	7.10216	$7,181	14%
Class 8 Mid Roof Sleeper Cab	78.0	7.66208	$7,175	14%
Class 8 High Roof Sleeper Cab	75.7	7.43615	$7,276	14%
Class 8 Heavy-Haul	52.4	5.14735	$5,063	8%
Trailers				
Long Dry Box Trailer	78.9	7.75049	$1,081	5%
Short Dry Box Trailer	123.7	12.15128	$772	2%
Long Refrigerated Box Trailer	80.6	7.91749	$1,081	5%
Short Refrigerated Box Trailer	127.5	12.52456	$772	2%
Vocational Diesel				
LHD Urban	424	41.6503	$1,106	12%
LHD Multi-Purpose	373	36.6405	$1,164	11%
LHD Regional	311	30.5501	$873	7%
MHD Urban	296	29.0766	$1,116	11%
MHD Multi-Purpose	265	26.0314	$1,146	10%
MHD Regional	234	22.9862	$851	6%
HHD Urban	308	30.2554	$1,334	9%
HHD Multi-Purpose	261	25.6385	$1,625	9%
HHD Regional	205	20.1375	$2,562	7%
Vocational Gasoline				
LHD Urban	461	51.8735	$1,106	8%
LHD Multi-Purpose	407	45.7972	$1,164	8%
LHD Regional	335	37.6955	$873	6%
MHD Urban	328	36.9078	$1,116	7%
MHD Multi-Purpose	293	32.9695	$1,146	7%
MHD Regional	261	29.3687	$851	5%

Source: U.S. EPA/NHSTA RIA.

Table 4-2: RIA Estimates for 2024 Fuel Economy by Class (Reproduced From RIA)

REGULATORY SUBCATEGORY	CO_2 GRAMS PER TON-MILE	FUEL CONSUMPTION GALLON PER 1,000 TON-MILE	AVERAGE INCREMENTAL COST PER VEHICLE RELATIVE TO PHASE 1 COSTS IN MODEL YEAR 2024 [A]	AVERAGE PERCENT FUEL CONSUMPTION AND CO_2 IMPROVEMENT IN MY 2024 RELATIVE TO MY 2017
Tractors				
Class 7 Low Roof Day Cab	99.8	9.80354	$8,037	16%
Class 7 Mid Roof Day Cab	107.1	10.52063	$8,037	16%
Class 7 High Roof Day Cab	106.6	10.47151	$8,210	18%
Class 8 Low Roof Day Cab	76.2	7.48527	$8,201	17%
Class 8 Mid Roof Day Cab	80.9	7.94695	$8,201	16%
Class 8 High Roof Day Cab	80.4	7.89784	$8,358	18%
Class 8 Low Roof Sleeper Cab	68.0	6.67976	$11,100	19%
Class 8 Mid Roof Sleeper Cab	73.5	7.22004	$11,100	19%
Class 8 High Roof Sleeper Cab	70.7	6.94499	$11,306	19%
Class 8 Heavy-Haul	50.2	4.93124	$7,937	12%
Trailers				
Long Dry Box Trailer	77.2	7.58350	$1,204	7%
Short Dry Box Trailer	120.9	11.87623	$1,171	4%
Long Refrigerated Box Trailer	78.9	7.75049	$1,204	7%
Short Refrigerated Box Trailer	124.7	12.24951	$1,171	4%
Vocational Diesel				
LHD Urban	385	37.8193	$1,959	20%
LHD Multi-Purpose	344	33.7917	$2,018	18%
LHD Regional	296	29.0766	$1,272	11%
MHD Urban	271	26.6208	$2,082	18%
MHD Multi-Purpose	246	24.1650	$2,110	16%
MHD Regional	221	21.7092	$1,274	11%
HHD Urban	283	27.7996	$2,932	16%
HHD Multi-Purpose	242	23.7721	$3,813	16%
HHD Regional	194	19.0570	$4,009	12%
Vocational Gasoline				
LHD Urban	432	48.6103	$1,959	13%
LHD Multi-Purpose	385	43.3217	$2,018	9%
LHD Regional	324	36.4577	$1,272	12%
MHD Urban	310	34.8824	$2,082	11%
MHD Multi-Purpose	279	31.3942	$2,110	9%
MHD Regional	251	28.2435	$1,274	13%

Source: U.S. EPA/NHSTA RIA.

Table 4-3: RIA Estimates for 2027 Fuel Economy by Class (Reproduced From RIA)

REGULATORY SUBCATEGORY	CO_2 GRAMS PER TON-MILE (FOR HD PUV, GRAMS PER MILE)	FUEL CONSUMPTION GALLON PER 1,000 TON-MILE (FOR HD PUV, GALLONS PER 100 MILES)	AVERAGE INCREMENTAL COST PER VEHICLE RELATIVE TO PHASE 1 COSTS IN MODEL YEAR 2027 [A]	AVERAGE PERCENT FUEL CONSUMPTION AND CO_2 IMPROVEMENT IN MY 2027 RELATIVE TO MY 2017
Tractors				
Class 7 Low Roof Day Cab	96.2	9.44990	$10,235	19%
Class 7 Mid Roof Day Cab	103.4	10.15717	$10,235	19%
Class 7 High Roof Day Cab	100.0	9.82318	$10,298	21%
Class 8 Low Roof Day Cab	73.4	7.21022	$10,439	20%
Class 8 Mid Roof Day Cab	78.0	7.66208	$10,439	19%
Class 8 High Roof Day Cab	75.7	7.43615	$10,483	22%
Class 8 Low Roof Sleeper Cab	64.1	6.29666	$13,535	24%
Class 8 Mid Roof Sleeper Cab	69.6	6.83694	$13,574	23%
Class 8 High Roof Sleeper Cab	64.3	6.31631	$13,749	25%
Class 8 Heavy-Haul	48.3	4.74460	$9,986	15%
Trailers				
Long Dry Box Trailer	75.7	7.43615	$1,370	9%
Short Dry Box Trailer	119.4	11.72888	$1,204	6%
Long Refrigerated Box Trailer	77.4	7.60314	$1,370	9%
Short Refrigerated Box Trailer	123.2	12.10216	$1,204	5%
Vocational Diesel				
LHD Urban	367	36.0511	$2,533	24%
LHD Multi-Purpose	330	32.4165	$2,571	21%
LHD Regional	291	28.5855	$1,486	13%
MHD Urban	258	25.3438	$2,727	22%
MHD Multi-Purpose	235	23.0845	$2,771	20%
MHD Regional	218	21.4145	$1,500	12%
HHD Urban	269	26.4244	$4,151	20%
HHD Multi-Purpose	230	22.5933	$5,025	20%
HHD Regional	189	18.5658	$5,670	14%
Vocational Gasoline				
LHD Urban	413	46.4724	$2,533	18%
LHD Multi-Purpose	372	41.8589	$2,571	16%
LHD Regional	319	35.8951	$1,486	11%
MHD Urban	297	33.4196	$2,727	16%
MHD Multi-Purpose	268	30.1564	$2,771	15%
MHD Regional	247	27.7934	$1,500	10%
Class 2b and 3 HD Pickups and Vans[b]				
HD Pickup and Van	460	4.88	$1,486	17%

Source: U.S. EPA/NHSTA RIA.

Table 4-4: RIA Estimates for 2021 to 2027 Fuel Economy – Custom Chassis (Reproduced From RIA)

REGULATORY SUBCATEGORY	CO_2 GRAMS PER TON-MILE	FUEL CONSUMPTION GALLON PER 1,000 TON-MILE	AVERAGE INCREMENTAL COST PER VEHICLE RELATIVE TO PHASE 1 COSTS IN MODEL YEAR 2021 [A]	AVERAGE PERCENT FUEL CONSUMPTION AND CO_2 IMPROVEMENT IN MY 2021 RELATIVE TO MY 2017
Vocational Custom Chassis				
Coach Bus	210	20.6287	900	7%
Motor Home	228	22.3969	600	6%
School Bus	291	28.5855	800	10%
Transit	300	29.4695	1000	7%
Refuse	313	30.7466	700	4%
Mixer	319	31.3360	300	3%
Emergency	324	31.8271	400	1%

REGULATORY SUBCATEGORY	CO_2 GRAMS PER TON-MILE	FUEL CONSUMPTION GALLON PER 1,000 TON-MILE	AVERAGE INCREMENTAL COST PER VEHICLE RELATIVE TO PHASE 1 COSTS IN MODEL YEAR 2027 [A]	AVERAGE PERCENT FUEL CONSUMPTION AND CO_2 IMPROVEMENT IN MY 2027 RELATIVE TO MY 2017
Vocational Custom Chassis				
Coach Bus	205	20.1375	1400	11%
Motor Home	226	22.2004	900	9%
School Bus	271	26.6208	1300	18%
Transit	286	28.0943	1800	14%
Refuse	298	29.2731	1300	12%
Mixer	316	31.0413	600	7%
Emergency	319	31.3360	600	6%

Source: U.S. EPA/NHSTA RIA.

Forecast of Vehicle Prices

Base-year prices for vehicles in each class were determined from three sources. First, Energy Commission staff had collected some retail prices for vehicles in specific classes. Second, manufacturer websites provided MSRP information on models for many vehicle classes from Class 3 to Class 7. Third, reports by transit and bus association provided price information that was anecdotal (citing transit or bus company staff). Prices for alternative fuel (CNG, propane, and electric) vehicles were based on the information listed in Chapter 3 on price increments added to the base price of the diesel or gasoline vehicle in the market. In the case of transit buses, the CARB provided[20] a set of price estimates for transit buses with diesel, diesel-electric hybrid, CNG, battery–electric, and fuel cell powertrains. The base year diesel bus price reported by CARB is higher than reported in other areas, and prices for hybrid, battery-electric, and fuel cell buses reflect extremely low volume (or pilot) production status. The volume production[21] and pilot production costs for electric and fuel cell vehicles are reported to Energy Commission in two scenarios.

The "learning curve" or "experience curve" describes the reduction in unit production costs as a function of accumulated production volume. The curve describes costs as a function of cumulative production volume measured at the level of a manufacturer, although it is often assumed—as both EPA and NHTSA have done in past regulatory analyses—to apply industrywide, particularly in industries that use many common technologies and component supply sources. Research into the costs of manufacturing has consistently shown that, as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower-cost materials, and reduce the number or complexity of component parts. All these factors allow manufacturers to lower the per-unit cost of production (that is, the manufacturing learning curve).

In past rulemaking analyses, as noted above, EPA and NHTSA have used a learning curve algorithm that applied a learning factor of 20 percent for each doubling of production volume. For example, NHTSA has used this approach in analyses supporting recent corporate average fuel economy (CAFE) rules. This is, however, different from scale economies, as the RIA estimates apply uniformly to high-volume production. Scale effects are associated with changes in processes going from low- to high-volume production. At very low volumes, components are individually manufactured, and assembly is by skilled workers. At high volumes, components use highly automated production, and vehicles are produced in assembly lines. The general experience is that each order of magnitude change in annual production volume changes the manufacturing method and results in a 30 percent cost decrease at the same level of technology. If pilot production is at 100 units per year, direct manufacturing costs will decrease by 30 percent as production volumes increase to 1,000 per year and by another

20 CARB Mobile Source Control Division. May 2017. "Advanced Clean Transit," presentation to the board.
21 For this report, *volume production* is defined as global sales of at least 10,000 units per year.

30 percent when production hits roughly 10,000 per year. Thus, high-volume costs cited by the EPA in the RIA are 49 percent (or 0.7*0.7) of pilot production costs. Of course, this is a general estimate as the exact reduction will be based on the level of production automation possible and material costs for the components themselves, which may be high for items like batteries or fuel cells. In addition, overheads and fixed cost amortization decline as the inverse of production volume.

A detailed analysis of low-volume costs was not possible in this effort, and as a result, the low-volume costs were based on actual MSRP cited by manufacturers for alternative fuel vehicles, whereas high volume costs are based on the data presented in in Chapter 3.

Forecasts

HDS provided forecasts for two scenarios. The first is a high electricity demand case that assumes electric vehicles are successful and uses the high-volume forecast of electric vehicle prices. The second is a low electricity demand case that uses the current (low-volume) prices of electric vehicles and assumes benefits of learning but not of scale (high-volume) for the forecast. The low case also uses the higher transit bus prices from the CARB as the starting point for prices in 2017 and assumes benefits of learning but not of scale for the forecast. The forecasts are shown in Tables 4-5 and 4-6, respectively.

The forecasts project that for all internal combustion engine-powered vehicles from 2017 to 2030:

- Vehicles in Classes 3 and 4 (mostly large pickups and vans) will increase fuel economy by about 25 to 29 percent.
- Medium-duty trucks in Classes 6 and 7 that operate in mixed suburban and urban routes will increase fuel economy by 22 to 25 percent.
- Vehicles in mostly urban use like garbage trucks and urban buses will have improvements in fuel economy of 9 to 12 percent.
- Long-haul trucks in Classes 7 and 8 will see the largest improvement of 29 to 32 percent in fuel economy.

The forecasts in Tables 4.5 and 4.6 project improvements in fuel economy (in miles per gallon), while the EPA forecasts decrease in fuel consumption (a 25 percent fuel consumption decrease is a 33.3 percent increase in fuel economy). Electric vehicles in each class will see smaller improvements in fuel efficiency because the electric motor is already very efficient and future gains in efficiency will be small; hence, most of the efficiency improvement is associated with improvements to body technology. Costs of electric vehicles, however, are forecast to decline mostly due to battery cost reduction and improved economies of scale.

Table 4-5: Forecast Vehicle Attribute Data Worksheet for High Electricity Demand Case

	Attribute	Unit	Type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CLASS 3 GASOLINE	Fuel economy	MPGG	OEM	14.90	15.10	15.30	15.80	16.30	16.73	17.16	17.59	18.02	18.34	18.65	18.97	19.15	19.33
	Price	2017 $		42,500	42,700	42,900	43,050	43,250	43,300	43,350	43,400	43,525	43,650	43,775	43,900	43,950	44,000
CLASS 3 DIESEL	Fuel economy	MPDG	OEM	17.45	17.66	17.87	18.10	18.32	18.81	19.30	19.78	20.27	20.63	20.99	21.35	21.45	21.55
	Price	2017 $		49,900	50,100	50,300	50,450	50,650	50,700	50,750	50,800	50,925	51,050	51,175	51,300	51,350	51,400
CLASS 3 E85	Fuel economy	MPEG	OEM	10.73	10.87	11.02	11.38	11.74	12.05	12.36	12.66	12.97	13.20	13.43	13.66	13.79	13.92
	Price	2017 $		42,500	42,700	42,900	43,050	43,250	43,300	43,350	43,400	43,525	43,650	43,775	43,900	43,950	44,000
CLASS 3 CNG	Fuel economy	MPGGE	AFM	14.16	14.35	14.54	15.01	15.49	15.89	16.30	16.71	17.12	17.42	17.72	18.02	18.19	18.36
	Price	2017 $		55,000	55,200	55,400	55,550	55,750	55,800	55,850	55,900	56,025	56,150	56,275	56,400	56,450	56,500
CLASS 3 LPG	Fuel economy	MPPG	AFM	11.29	11.45	11.60	11.98	12.36	12.68	13.01	13.33	13.66	13.90	14.14	14.38	14.52	14.65
	Price	2017 $		53,500	53,700	53,900	54,050	54,250	54,300	54,350	54,400	54,525	54,650	54,775	54,900	54,950	55,000
CLASS 3 EL.HYBRID	Fuel economy	MPGG	OEM				20.86	21.52	22.08	22.65	23.22	23.79	24.20	24.62	25.04	25.28	25.52
	Price	2017 $					49,550	49,555	49,416	49,282	49,154	49,107	49,064	49,027	48,994	48,892	48,793
CLASS 3 BEV	Fuel economy	MPKWH	OEM	1.20	1.21	1.22	1.24	1.25	1.26	1.27	1.29	1.30	1.31	1.33	1.34	1.35	1.37
	Price	2017 $		63,500	62,650	61,853	61,055	60,355	59,549	58,787	58,065	57,457	56,885	56,348	55,845	55,298	54,780
CLASS 3 MOTORHOME GAS	Fuel economy	MPGG	AFM	14.16	14.35	14.54	15.01	15.49	15.89	16.30	16.71	17.12	17.42	17.72	18.02	18.19	18.36
	Price	2017 $		107,500	107,700	107,900	108,050	108,250	108,300	108,350	108,400	108,525	108,650	108,775	108,900	108,950	109,000
CLASS 3 MOTORHOME DIESEL	Fuel economy	MPDG	AFM	16.58	16.78	16.98	17.20	17.40	17.87	18.33	18.79	19.26	19.60	19.94	20.28	20.38	20.47
	Price	2017 $		114,500	114,700	114,900	115,050	115,250	115,300	115,350	115,400	115,525	115,650	115,775	115,900	115,950	116,000
CLASS 4 /5 GASOLINE	Fuel economy	MPGG	OEM	6.9	7.09	7.28	7.47	7.66	7.81	7.95	8.10	8.19	8.29	8.38	8.45	8.51	8.58
	Price	2017 $		46,400	46,690	46,980	47,270	47,560	47,847	48,133	48,420	48,603	48,787	48,970	49,047	49,123	49,200
CLASS 4/5 DIESEL	Fuel economy	MPDG	OEM	8.63	8.87	9.11	9.34	9.58	9.85	10.11	10.38	10.53	10.67	10.82	10.90	10.98	11.06
	Price	2017 $		54,300	54,590	54,880	55,170	55,460	55,747	56,033	56,320	56,503	56,687	56,870	56,963	57,057	57,150
CLASS 4/5 E85	Fuel economy	MPEG	OEM	4.97	5.10	5.24	5.38	5.52	5.62	5.73	5.83	5.90	5.97	6.03	6.08	6.13	6.18
	Price	2017 $		46,400	46,690	46,980	47,270	47,560	47,847	48,133	48,420	48,603	48,787	48,970	49,047	49,123	49,200
CLASS 4/5 CNG	Fuel economy	MPGGE	AFM	6.56	6.74	6.92	7.10	7.28	7.42	7.56	7.70	7.78	7.87	7.96	8.02	8.09	8.15
	Price	2017 $		58,900	59,190	59,480	59,770	60,060	60,347	60,633	60,920	61,103	61,287	61,470	61,547	61,623	61,700
CLASS 4/5 LPG	Fuel economy	MPGGE	AFM	5.23	5.37	5.52	5.66	5.81	5.92	6.03	6.14	6.21	6.28	6.35	6.40	6.45	6.50
	Price	2017 $		57,400	57,690	57,980	58,270	58,560	58,847	59,133	59,420	59,603	59,787	59,970	60,047	60,123	60,200
CLASS 4/5 EL.HYBRID	Fuel economy	MPGG	OEM				9.86	10.11	10.30	10.50	10.69	10.82	10.94	11.06	11.15	11.24	11.33
	Price	2017 $					54,770	54,835	54,903	54,978	55,060	55,044	55,034	55,030	54,925	54,825	54,731

	Attribute	Unit	Type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CLASS 4/5 DIESEL HH	Fuel economy	MPDG	OEM	10.79	11.08	11.38	11.68	11.98	12.31	12.64	12.98	13.16	13.34	13.53	13.63	13.73	13.83
	Price	2017 $		78,300	78,590	78,880	79,170	79,460	79,747	80,033	80,320	80,503	80,687	80,870	80,963	81,057	81,150
CLASS 4/5 BEV	Fuel economy	MPKWH	OEM	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.13	1.14	1.15	1.16	1.17	1.18	1.19
	Price	2017 $		70,900	69,965	69,091	68,276	67,515	66,804	66,143	65,529	64,857	64,228	63,639	62,982	62,362	61,777
CLASS 6 DIESEL	Fuel economy	MPDG	OEM	6.24	6.40	6.55	6.71	6.86	7.04	7.21	7.39	7.50	7.62	7.73	7.77	7.81	7.85
	Price	2017 $		55,300	55,588	55,875	56,163	56,450	56,770	57,090	57,410	57,630	57,850	58,070	58,213	58,357	58,500
CLASS 6 DIESEL EL. HYBRID	Fuel economy	MPDG	OEM	7.49	7.67	7.86	8.05	8.23	8.44	8.66	8.87	9.00	9.14	9.28	9.32	9.37	9.42
	Price	2017 $		75,300	74,988	74,693	74,416	74,156	73,945	73,749	73,570	73,305	73,055	72,818	72,519	72,234	71,961
CLASS 6 DIESEL HY. HYBRID	Fuel economy	MPDG	AFM	7.36	7.55	7.73	7.91	8.09	8.30	8.51	8.72	8.85	8.99	9.12	9.17	9.22	9.26
	Price	2017 $		79,300	79,588	79,875	80,163	80,450	80,770	81,090	81,410	81,630	81,850	82,070	82,213	82,357	82,500
CLASS 6 CNG	Fuel economy	MPDG	AFM	5.30	5.44	5.57	5.70	5.83	5.98	6.13	6.28	6.38	6.47	6.57	6.60	6.64	6.67
	Price	2017 $		90,300	90,588	90,875	91,163	91,450	91,770	92,090	92,410	92,630	92,850	93,070	93,213	93,357	93,500
CLASS 6 BEV	Fuel economy	MPKWH	OEM	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03
	Price	2017 $		85,800	85,173	84,572	83,999	83,451	82,961	82,496	82,053	81,534	81,037	80,561	80,030	79,519	79,027
CLASS 6 MOTORHOME DIESEL	Fuel economy	MPDG	AFM	7.33	7.44	7.55	7.66	7.77	7.92	8.07	8.22	8.26	8.30	8.34	8.36	8.38	8.40
	Price	2017 $		142,000	142,213	142,425	142,638	142,850	142,992	143,133	143,275	143,350	143,425	143,500	143,533	143,567	143,600
CLASS 6 MOTORHOME GASOLINE	Fuel economy	MPGG	AFM	5.79	5.86	5.94	6.01	6.08	6.16	6.24	6.32	6.36	6.39	6.43	6.46	6.49	6.52
	Price	2017 $		134,000	134,213	134,425	134,638	134,850	134,992	135,133	135,275	135,350	135,425	135,500	135,550	135,600	135,650
CLASS 7 SINGLE UNIT DIESEL	Fuel economy	MPDG	OEM	6.96	7.15	7.34	7.53	7.72	7.87	8.01	8.16	8.26	8.36	8.47	8.49	8.52	8.55
	Price	2017 $		93,400	94,684	95,967	97,251	98,534	99,502	100,469	101,437	102,170	102,902	103,635	103,723	103,812	103,900
CLASS 7 DIESEL ELECTRIC HYBRID	Fuel economy	MPDG	OEM				8.43	8.65	8.81	8.97	9.14	9.25	9.37	9.48	9.51	9.54	9.58
	Price	2017 $					133,251	133,454	133,374	133,326	133,308	133,084	132,889	132,722	131,938	131,180	130,447
CLASS 7 CNG	Fuel economy	MPDGE	AFM	5.98	6.15	6.31	6.47	6.64	6.77	6.89	7.02	7.11	7.19	7.28	7.30	7.33	7.35
	Price	2017 $		128,400	129,684	130,967	132,251	133,534	134,502	135,469	136,437	137,170	137,902	138,635	138,723	138,812	138,900
CLASS 8 SINGLE UNIT DIESEL	Fuel economy	MPDG	OEM	4.77	4.88	4.99	5.09	5.20	5.34	5.47	5.61	5.71	5.80	5.90	5.92	5.94	5.96
	Price	2017 $		96,950	97,363	97,775	98,188	98,600	99,333	100,067	100,800	101,192	101,583	101,975	102,150	102,325	102,500
CLASS 8 SINGLE UNIT CNG	Fuel economy	MPDGE	AFM	4.10	4.19	4.29	4.38	4.47	4.59	4.71	4.82	4.91	4.99	5.07	5.09	5.11	5.13
	Price	2017 $		151,950	152,363	152,775	153,188	153,600	154,333	155,067	155,800	156,192	156,583	156,975	157,150	157,325	157,500
CLASS 8 SINGLE UNIT LNG	Fuel economy	MPDGE	AFM	4.10	4.19	4.29	4.38	4.47	4.59	4.71	4.82	4.91	4.99	5.07	5.09	5.11	5.13
	Price	2017 $		161,950	162,363	162,775	163,188	163,600	164,333	165,067	165,800	166,192	166,583	166,975	167,150	167,325	167,500
CLASS 8 CA COMBINATION DIESEL	Fuel economy	MPDGE	OEM	5.54	5.72	5.90	6.08	6.26	6.36	6.46	6.56	6.69	6.82	6.95	6.98	7.02	7.05
	Price	2017 $		119,500	120,830	122,160	123,490	124,820	125,500	126,180	126,860	127,273	127,687	128,780	128,887	128,993	129,100

	Attribute	Unit	Type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CLASS 8 CA COMBINATION CNG	Fuel economy	MPDGE	AFM	5.26	5.43	5.61	5.78	5.95	6.04	6.14	6.23	6.36	6.48	6.60	6.63	6.67	6.70
	Price	2017 $		194,500	195,830	197,160	198,490	199,820	200,500	201,180	201,860	202,273	202,687	203,780	203,887	203,993	204,100
CLASS 8 CA COMBINATION LNG	Fuel economy	MPDGE	AFM	5.26	5.43	5.61	5.78	5.95	6.04	6.14	6.23	6.36	6.48	6.60	6.63	6.67	6.70
	Price	2017 $		204,500	205,830	207,160	208,490	209,820	210,500	211,180	211,860	212,273	212,687	213,780	213,887	213,993	214,100
CLASS 8 CA COMBINATION EL	Fuel economy	MPKWH	AFM			0.280	0.295	0.310	0.313	0.315	0.318	0.323	0.327	0.332	0.333	0.334	0.335
(Direct / Catenary Electric)	Price	2017 $				132,160	133,160	134,160	134,690	135,220	135,750	136,260	136,770	137,280	137,353	137,427	137,500
CLASS 8 CA COMBINATION FC	Fuel economy	MPKGH2	AFM			5.82	6.14	6.45	6.50	6.56	6.61	6.71	6.80	6.90	6.92	6.94	6.96
(Fuel Cell)	Price	2017 $				207,160	206,790	206,454	205,501	204,581	203,693	202,570	201,477	201,095	199,755	198,445	197,162
CLASS 8 COMBINATION DIESEL	Fuel economy	MPDGE	OEM	6.21	6.41	6.62	6.82	7.02	7.16	7.31	7.45	7.68	7.90	8.13	8.14	8.15	8.16
	Price	2017 $		142,000	143,818	145,635	147,453	149,270	150,530	151,790	153,050	153,533	154,017	154,500	154,700	154,900	155,100
CLASS 8 COMBINATION CNG	Fuel economy	MPDGE	OEM	5.90	6.09	6.28	6.48	6.67	6.81	6.94	7.08	7.29	7.51	7.72	7.73	7.74	7.75
	Price	2017 $		217,000	218,818	220,635	222,453	224,270	225,530	226,790	228,050	228,533	229,017	229,500	229,700	229,900	230,100
CLASS 8 COMBINATION LNG	Fuel economy	MPDGE	OEM	5.60	5.79	5.97	6.15	6.34	6.46	6.59	6.72	6.93	7.13	7.34	7.35	7.36	7.36
	Price	2017 $		302,000	303,818	305,635	307,453	309,270	310,530	311,790	313,050	313,533	314,017	314,500	314,700	314,900	315,100
CLASS 8 GARBAGE DIESEL	Fuel economy	MPDGE	OEM	4.22	4.25	4.28	4.31	4.34	4.37	4.41	4.44	4.48	4.51	4.55	4.57	4.59	4.61
	Price	2017 $		191,600	191,933	192,265	192,598	192,930	193,463	193,997	194,530	194,937	195,343	195,750	195,900	196,050	196,200
CLASS 8 GARBAGE DIESEL EL. HYBRID	Fuel economy	MPDG	OEM	5.06	5.10	5.14	5.17	5.21	5.25	5.29	5.33	5.37	5.42	5.46	5.48	5.51	5.53
	Price	2017 $		231,600	230,733	229,901	229,104	228,342	227,813	227,316	226,849	226,286	225,753	225,247	224,512	223,804	223,121
CLASS 8 GARBAGE DIESEL HY. HYBRID	Fuel economy	MPDG	AFM	4.98	5.02	5.05	5.09	5.12	5.16	5.20	5.24	5.28	5.33	5.37	5.39	5.42	5.44
	Price	2017 $		226,600	226,933	227,265	227,598	227,930	228,463	228,997	229,530	229,937	230,343	230,750	230,900	231,050	231,200
CLASS 8 GARBAGE CNG	Fuel economy	MPDG	AFM	3.59	3.61	3.64	3.66	3.69	3.72	3.75	3.77	3.81	3.84	3.87	3.88	3.90	3.92
	Price	2017 $		246,600	246,933	247,265	247,598	247,930	248,463	248,997	249,530	249,937	250,343	250,750	250,900	251,050	251,200
CLASS 8 GARBAGE LNG	Fuel economy	MPDG	AFM	3.59	3.61	3.64	3.66	3.69	3.72	3.75	3.77	3.81	3.84	3.87	3.88	3.90	3.92
	Price	2017 $		256,600	256,933	257,265	257,598	257,930	258,463	258,997	259,530	259,937	260,343	260,750	260,900	261,050	261,200
URBAN TRANSIT DIESEL	Fuel economy	MPGD	OEM	3.42	3.45	3.47	3.50	3.52	3.56	3.60	3.64	3.67	3.71	3.75	3.77	3.78	3.80
	Price	2017 $		250,000	250,333	250,665	250,998	251,330	251,800	252,270	252,740	253,210	253,680	254,150	254,267	254,383	254,500
URBAN TRANSIT DIESEL EL HYBRID	Fuel economy	MPGD	AFM	4.55	4.58	4.62	4.65	4.68	4.73	4.78	4.83	4.89	4.94	4.99	5.01	5.03	5.05
	Price	2017 $		290,000	289,133	288,301	287,504	286,742	286,149	285,589	285,059	284,560	284,089	283,647	282,879	282,137	281,421
URBAN TRANSIT DIESEL HY. HYBRID	Fuel economy	MPGD	AFM	4.28	4.31	4.34	4.37	4.40	4.45	4.50	4.54	4.59	4.64	4.69	4.71	4.73	4.75
	Price	2017 $		285,000	285,333	285,665	285,998	286,330	286,800	287,270	287,740	288,210	288,680	289,150	289,267	289,383	289,500
URBAN TRANSIT CNG	Fuel economy	MPDGE	AFM	2.91	2.93	2.95	2.97	2.99	3.02	3.06	3.09	3.12	3.15	3.19	3.20	3.22	3.23
	Price	2017 $		305,000	305,333	305,665	305,998	306,330	306,800	307,270	307,740	308,210	308,680	309,150	309,267	309,383	309,500

	Attribute	Unit	Type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
URBAN TRANSIT BEV	Fuel economy	MPKWH	OEM	0.250	0.251	0.251	0.252	0.252	0.253	0.253	0.254	0.254	0.255	0.255	0.256	0.256	0.257
	Price	2017 $		500,000	495,333	490,765	486,296	481,922	477,780	473,731	469,771	465,901	462,117	458,418	454,450	450,563	446,756
URBAN TRANSIT FCEV	Fuel economy	MPKGH2	OEM					5.16	5.17	5.18	5.19	5.20	5.21	5.22	5.23	5.24	5.25
	Price	2017 $						501,330	496,800	492,370	488,038	483,802	479,660	475,611	471,298	467,074	462,937
SHUTTLE BUS GASOLINE	Fuel economy	MPGG	OEM	6.9	7.09	7.28	7.47	7.66	7.81	7.95	8.10	8.19	8.29	8.38	8.45	8.51	8.58
	Price	2017 $		76,400	76,690	76,980	77,270	77,560	77,847	78,133	78,420	78,603	78,787	78,970	79,047	79,123	79,200
SHUTTLE BUS DIESEL	Fuel economy	MPGD	OEM	8.63	8.87	9.11	9.34	9.58	9.85	10.11	10.38	10.53	10.67	10.82	10.90	10.98	11.06
	Price	2017 $		84,300	84,590	84,880	85,170	85,460	85,747	86,033	86,320	86,503	86,687	86,870	86,963	87,057	87,150
SHUTTLE BUS E85	Fuel economy	MPGE	OEM	4.97	5.10	5.24	5.38	5.52	5.62	5.73	5.83	5.90	5.97	6.03	6.08	6.13	6.18
	Price	2017 $		76,400	76,690	76,980	77,270	77,560	77,847	78,133	78,420	78,603	78,787	78,970	79,047	79,123	79,200
SHUTTLE BUS CNG	Fuel economy	MPGGE	AFM	6.56	6.74	6.92	7.10	7.28	7.42	7.56	7.70	7.78	7.87	7.96	8.02	8.09	8.15
	Price	2017 $		88,900	89,190	89,480	89,770	90,060	90,347	90,633	90,920	91,103	91,287	91,470	91,547	91,623	91,700
SHUTTLE BUS DIESEL HYD. HYBRID	Fuel economy	MPGP	AFM	10.53	10.82	11.11	11.40	11.69	12.01	12.34	12.66	12.84	13.02	13.20	13.30	13.40	13.49
	Price	2017 $		108,300	108,590	108,880	109,170	109,460	109,747	110,033	110,320	110,503	110,687	110,870	110,963	111,057	111,150
SHUTTLE BUS BEV	Fuel economy	MPKWH	OEM	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.13	1.14	1.15	1.16	1.17	1.18	1.19
	Price	2017 $		524,500	518,608	512,876	507,301	501,877	496,738	491,740	486,881	482,155	477,558	473,087	468,385	463,801	459,332
SCHOOL BUS GASOLINE	Fuel economy	MPGG	OEM	6.25	6.42	6.60	6.77	6.94	7.05	7.17	7.28	7.39	7.51	7.62	7.63	7.64	7.65
	Price	2017 $		77,300	77,588	77,875	78,163	78,450	78,770	79,090	79,410	79,630	79,850	80,070	80,213	80,357	80,500
SCHOOL BUS DIESEL	Fuel economy	MPGD	OEM	7.81	8.87	9.11	9.34	9.58	9.85	10.11	10.38	10.53	10.67	10.82	10.90	10.98	11.06
	Price	2017 $		85,300	85,588	85,875	86,163	86,450	86,770	87,090	87,410	87,630	87,850	88,070	88,213	88,357	88,500
SCHOOL BUS BEV	Fuel economy	MPKWH	OEM	0.904	0.913	0.922	0.931	0.941	0.950	0.960	0.969	0.979	0.989	0.999	1.009	1.019	1.029
	Price	2017 $		112,300	111,538	110,807	110,106	109,435	108,826	108,244	107,689	107,061	106,458	105,880	105,249	104,641	104,056
SCHOOL BUS CNG	Fuel economy	MPGGE	AFM	5.94	6.10	6.27	6.43	6.59	6.70	6.81	6.92	7.02	7.13	7.24	7.25	7.26	7.27
	Price	2017 $		97,300	97,588	97,875	98,163	98,450	98,770	99,090	99,410	99,630	99,850	100,070	100,213	100,357	100,500
SCHOOL BUS LPG	Fuel economy	MPGP	AFM	4.74	4.87	5.00	5.13	5.26	5.35	5.43	5.52	5.60	5.69	5.78	5.78	5.79	5.80
	Price	2017 $		95,300	105,588	105,875	106,163	106,450	106,770	107,090	107,410	107,630	107,850	108,070	108,213	108,357	108,500
MOTOR COACH DIESEL	Fuel economy	MPDG	OEM	6.96	7.15	7.34	7.53	7.72	7.87	8.01	8.16	8.26	8.36	8.47	8.49	8.52	8.55
	Price	2017 $		350,000	351,284	352,567	353,851	355,134	356,102	357,069	358,037	358,770	359,502	360,235	360,323	360,412	360,500
MOTOR COACH CNG	Fuel economy	MPDGE	OEM	5.91	6.07	6.24	6.40	6.56	6.69	6.81	6.94	7.02	7.11	7.20	7.22	7.24	7.27
	Price	2017 $		385,000	386,284	387,567	388,851	390,134	391,102	392,069	393,037	393,770	394,502	395,235	395,323	395,412	395,500

Source: H-D Systems.

Table 4-6: Forecast Vehicle Attribute Data Worksheet for Low Electricity Demand Case

	Attribute	unit	type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CLASS 3 GASOLINE	Fuel economy	MPGG	OEM	14.90	15.10	15.30	15.80	16.30	16.73	17.16	17.59	18.02	18.34	18.65	18.97	19.15	19.33
	Price	2017 $		42,500	42,700	42,900	43,050	43,250	43,300	43,350	43,400	43,525	43,650	43,775	43,900	43,950	44,000
CLASS 3 DIESEL	Fuel economy	MPDG	OEM	17.45	17.66	17.87	18.10	18.32	18.81	19.30	19.78	20.27	20.63	20.99	21.35	21.45	21.55
	Price	2017 $		49,900	50,100	50,300	50,450	50,650	50,700	50,750	50,800	50,925	51,050	51,175	51,300	51,350	51,400
CLASS 3 E85	Fuel economy	MPEG	OEM	10.73	10.87	11.02	11.38	11.74	12.05	12.36	12.66	12.97	13.20	13.43	13.66	13.79	13.92
	Price	2017 $		42,500	42,700	42,900	43,050	43,250	43,300	43,350	43,400	43,525	43,650	43,775	43,900	43,950	44,000
CLASS 3 CNG	Fuel economy	MPGGE	AFM	14.16	14.35	14.54	15.01	15.49	15.89	16.30	16.71	17.12	17.42	17.72	18.02	18.19	18.36
	Price	2017 $		55,000	55,200	55,400	55,550	55,750	55,800	55,850	55,900	56,025	56,150	56,275	56,400	56,450	56,500
CLASS 3 LPG	Fuel economy	MPGP	AFM	11.29	11.45	11.60	11.98	12.36	12.68	13.01	13.33	13.66	13.90	14.14	14.38	14.52	14.65
	Price	2017 $		53,500	53,700	53,900	54,050	54,250	54,300	54,350	54,400	54,525	54,650	54,775	54,900	54,950	55,000
CLASS 3 EL.HYBRID	Fuel economy	MPGG	OEM				20.86	21.52	22.08	22.65	23.22	23.79	24.20	24.62	25.04	25.28	25.52
	Price	2017 $					49,550	49,555	49,416	49,282	49,154	49,107	49,064	49,027	48,994	48,892	48,793
CLASS 3 BEV	Fuel economy	MPKWH	OEM	1.20	1.21	1.22	1.24	1.25	1.26	1.27	1.29	1.30	1.31	1.33	1.34	1.35	1.37
	Price	2017 $		84,500	82,600	80,805	79,060	77,459	75,799	74,224	72,730	71,389	70,120	68,922	67,790	66,645	65,560
CLASS 3 MOTORHOME GAS	Fuel economy	MPGG	AFM	14.16	14.35	14.54	15.01	15.49	15.89	16.30	16.71	17.12	17.42	17.72	18.02	18.19	18.36
	Price	2017 $		107,500	107,700	107,900	108,050	108,250	108,300	108,350	108,400	108,525	108,650	108,775	108,900	108,950	109,000
CLASS 3 MOTORHOME DIESEL	Fuel economy	MPDG	AFM	16.58	16.78	16.98	17.20	17.40	17.87	18.33	18.79	19.26	19.60	19.94	20.28	20.38	20.47
	Price	2017 $		114,500	114,700	114,900	115,050	115,250	115,300	115,350	115,400	115,525	115,650	115,775	115,900	115,950	116,000
CLASS 4 /5 GASOLINE	Fuel economy	MPGG	OEM	6.9	7.09	7.28	7.47	7.66	7.81	7.95	8.10	8.19	8.29	8.38	8.45	8.51	8.58
	Price	2017 $		46,400	46,690	46,980	47,270	47,560	47,847	48,133	48,420	48,603	48,787	48,970	49,047	49,123	49,200
CLASS 4/5 DIESEL	Fuel economy	MPDG	OEM	8.63	8.87	9.11	9.34	9.58	9.85	10.11	10.38	10.53	10.67	10.82	10.90	10.98	11.06
	Price	2017 $		54,300	54,590	54,880	55,170	55,460	55,747	56,033	56,320	56,503	56,687	56,870	56,963	57,057	57,150
CLASS 4/5 E85	Fuel economy	MPEG	OEM	4.97	5.10	5.24	5.38	5.52	5.62	5.73	5.83	5.90	5.97	6.03	6.08	6.13	6.18
	Price	2017 $		46,400	46,690	46,980	47,270	47,560	47,847	48,133	48,420	48,603	48,787	48,970	49,047	49,123	49,200
CLASS 4/5 CNG	Fuel economy	MPGGE	AFM	6.56	6.74	6.92	7.10	7.28	7.42	7.56	7.70	7.78	7.87	7.96	8.02	8.09	8.15
	Price	2017 $		58,900	59,190	59,480	59,770	60,060	60,347	60,633	60,920	61,103	61,287	61,470	61,547	61,623	61,700
CLASS 4/5 LPG	Fuel economy	MPGGE	AFM	5.23	5.37	5.52	5.66	5.81	5.92	6.03	6.14	6.21	6.28	6.35	6.40	6.45	6.50
	Price	2017 $		57,400	57,690	57,980	58,270	58,560	58,847	59,133	59,420	59,603	59,787	59,970	60,047	60,123	60,200
CLASS 4/5 EL.HYBRID	Fuel economy	MPGG	OEM				9.86	10.11	10.30	10.50	10.69	10.82	10.94	11.06	11.15	11.24	11.33
	Price	2017 $					54,770	54,835	54,903	54,978	55,060	55,044	55,034	55,030	54,925	54,825	54,731

	Attribute	unit	type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CLASS 4/5 DIESEL HH	Fuel economy	MPDG	OEM	10.79	11.08	11.38	11.68	11.98	12.31	12.64	12.98	13.16	13.34	13.53	13.63	13.73	13.83
	Price	2017 $		78,300	78,590	78,880	79,170	79,460	79,747	80,033	80,320	80,503	80,687	80,870	80,963	81,057	81,150
CLASS 4/5 BEV	Fuel economy	MPKWH	OEM	1.050	1.061	1.071	1.082	1.093	1.104	1.115	1.126	1.137	1.148	1.160	1.171	1.183	1.195
	Price	2017 $		140,900	136,465	132,266	128,292	124,531	120,969	117,600	114,413	111,297	108,345	105,551	102,798	100,187	97,711
CLASS 6 GASOLINE	Fuel economy	MPGG	OEM	4.99	5.12	5.24	5.36	5.49	5.63	5.77	5.91	6.00	6.09	6.18	6.22	6.25	6.28
	Price	2017 $		58,300	58,588	58,875	59,163	59,450	59,770	60,090	60,410	60,630	60,850	61,070	61,213	61,357	61,500
CLASS 6 DIESEL	Fuel economy	MPDG	OEM	6.24	6.40	6.55	6.71	6.86	7.04	7.21	7.39	7.50	7.62	7.73	7.77	7.81	7.85
	Price	2017 $		67,300	67,588	67,875	68,163	68,450	68,770	69,090	69,410	69,630	69,850	70,070	70,213	70,357	70,500
CLASS 6 DIESEL EL. HYBRID	Fuel economy	MPDG	OEM	7.488	7.674	7.86	8.046	8.232	8.444	8.656	8.868	9.004	9.14	9.276	9.324	9.372	9.42
	Price	2017 $		87,300	86,988	86,693	86,416	86,156	85,945	85,749	85,570	85,305	85,055	84,818	84,519	84,234	83,961
CLASS 6 DIESEL HY. HYBRID	Fuel economy	MPDG	AFM	7.36	7.55	7.73	7.91	8.09	8.30	8.51	8.72	8.85	8.99	9.12	9.17	9.22	9.26
	Price	2017 $		91,300	91,588	91,875	92,163	92,450	92,770	93,090	93,410	93,630	93,850	94,070	94,213	94,357	94,500
CLASS 6 CNG	Fuel economy	MPDG	AFM	5.30	5.44	5.57	5.70	5.83	5.98	6.13	6.28	6.38	6.47	6.57	6.60	6.64	6.67
	Price	2017 $		102,300	102,588	102,875	103,163	103,450	103,770	104,090	104,410	104,630	104,850	105,070	105,213	105,357	105,500
CLASS 6 BEV	Fuel economy	MPKWH	OEM	0.904	0.913	0.922	0.931	0.941	0.950	0.960	0.969	0.979	0.989	0.999	1.009	1.019	1.029
	Price	2017 $		179,300	178,468	177,646	176,836	176,037	175,281	174,536	173,801	172,977	172,164	171,361	170,491	169,632	166,797
CLASS 6 MOTORHOME DIESEL	Fuel economy	MPDG	AFM	7.33	7.44	7.55	7.66	7.77	7.92	8.07	8.22	8.26	8.30	8.34	8.36	8.38	8.40
	Price	2017 $		142,000	142,213	142,425	142,638	142,850	142,992	143,133	143,275	143,350	143,425	143,500	143,533	143,567	143,600
CLASS 6 MOTORHOME GASOLINE	Fuel economy	MPGG	AFM	5.79	5.86	5.94	6.01	6.08	6.16	6.24	6.32	6.36	6.39	6.43	6.46	6.49	6.52
	Price	2017 $		134,000	134,213	134,425	134,638	134,850	134,992	135,133	135,275	135,350	135,425	135,500	135,550	135,600	135,650
CLASS 7 LR	Fuel economy	MPDG	OEM	6.96	7.15	7.34	7.53	7.72	7.87	8.01	8.16	8.26	8.36	8.47	8.49	8.52	8.55
	Price	2017 $		93,400	94,684	95,967	97,251	98,534	99,502	100,469	101,437	102,170	102,902	103,635	103,723	103,812	103,900
CLASS 7 EHEV	Fuel economy	MPDG	OEM				8.43	8.65	8.81	8.97	9.14	9.25	9.37	9.48	9.51	9.54	9.58
	Price						133,251	133,454	133,374	133,326	133,308	133,084	132,889	132,722	131,938	131,180	130,447
CLASS 7 CNG	Fuel economy	MPDGE	AFM	5.98	6.15	6.31	6.47	6.64	6.77	6.89	7.02	7.11	7.19	7.28	7.30	7.33	7.35
	Price	2017 $		128,400	129,684	130,967	132,251	133,534	134,502	135,469	136,437	137,170	137,902	138,635	138,723	138,812	138,900
CLASS 8 SINGLE UNIT	Fuel economy	MPDG	OEM	4.77	4.88	4.99	5.09	5.20	5.34	5.47	5.61	5.71	5.80	5.90	5.92	5.94	5.96
	Price	2017 $		96,950	97,363	97,775	98,188	98,600	99,333	100,067	100,800	101,192	101,583	101,975	102,150	102,325	102,500
CLASS 8 SINGLE UNIT CNG	Fuel economy	MPDGE	AFM	4.10	4.19	4.29	4.38	4.47	4.59	4.71	4.82	4.91	4.99	5.07	5.09	5.11	5.13
	Price	2017 $		151,950	152,363	152,775	153,188	153,600	154,333	155,067	155,800	156,192	156,583	156,975	157,150	157,325	157,500
CLASS 8 SINGLE UNIT LNG	Fuel economy	MPDGE	AFM	4.10	4.19	4.29	4.38	4.47	4.59	4.71	4.82	4.91	4.99	5.07	5.09	5.11	5.13
	Price	2017 $		161,950	162,363	162,775	163,188	163,600	164,333	165,067	165,800	166,192	166,583	166,975	167,150	167,325	167,500

	Attribute	unit	type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CLASS 8 CA COMBINATION	Fuel economy	MPDGE	OEM	5.54	5.72	5.90	6.08	6.26	6.36	6.46	6.56	6.69	6.82	6.95	6.98	7.02	7.05
	Price	2017 $		119,500	120,830	122,160	123,490	124,820	125,500	126,180	126,860	127,273	127,687	128,780	128,887	128,993	129,100
CLASS 8 CA COMBINATION CNG	Fuel economy	MPDGE	AFM	5.26	5.43	5.61	5.78	5.95	6.04	6.14	6.23	6.36	6.48	6.60	6.63	6.67	6.70
	Price	2017 $		194,500	195,830	197,160	198,490	199,820	200,500	201,180	201,860	202,273	202,687	203,780	203,887	203,993	204,100
CLASS 8 CA COMBINATION LNG	Fuel economy	MPDGE	AFM	5.26	5.43	5.61	5.78	5.95	6.04	6.14	6.23	6.36	6.48	6.60	6.63	6.67	6.70
	Price	2017 $		204,500	205,830	207,160	208,490	209,820	210,500	211,180	211,860	212,273	212,687	213,780	213,887	213,993	214,100
CLASS 8 CA COMBINATION EL	Fuel economy	MPKWH	AFM			0.280	0.295	0.310	0.313	0.315	0.318	0.323	0.327	0.332	0.333	0.334	0.335
(Direct / Catenary Electric)	Price	2017 $				162,160	163,160	164,160	164,690	165,220	165,750	166,260	166,770	167,280	167,353	167,427	167,500
CLASS 8 CA COMBINATION FC	Fuel economy	MPKGH2	AFM			5.82	6.14	6.45	6.50	6.56	6.61	6.71	6.80	6.90	6.92	6.94	6.96
(Fuel Cell)	Price	2017 $				207,160	206,790	206,454	205,501	204,581	203,693	202,570	201,477	201,095	199,755	198,445	197,162
CLASS 8 COMBINATION DIESEL	Fuel economy	MPDGE	OEM	6.21	6.41	6.62	6.82	7.02	7.16	7.31	7.45	7.68	7.90	8.13	8.14	8.15	8.16
	Price	2017 $		142,000	143,818	145,635	147,453	149,270	150,530	151,790	153,050	153,533	154,017	154,500	154,700	154,900	155,100
CLASS 8 COMBINATION CNG	Fuel economy	MPDGE	OEM	5.90	6.09	6.28	6.48	6.67	6.81	6.94	7.08	7.29	7.51	7.72	7.73	7.74	7.75
	Price	2017 $		217,000	218,818	220,635	222,453	224,270	225,530	226,790	228,050	228,533	229,017	229,500	229,700	229,900	230,100
CLASS 8 COMBINATION LNG	Fuel economy	MPDGE	OEM	5.60	5.79	5.97	6.15	6.34	6.46	6.59	6.72	6.93	7.13	7.34	7.35	7.36	7.36
	Price	2017 $		302,000	303,818	305,635	307,453	309,270	310,530	311,790	313,050	313,533	314,017	314,500	314,700	314,900	315,100
CLASS 8 GARBAGE DIESEL	Fuel economy	MPDGE	OEM	4.22	4.25	4.28	4.31	4.34	4.37	4.41	4.44	4.48	4.51	4.55	4.57	4.59	4.61
	Price	2017 $		191,600	191,933	192,265	192,598	192,930	193,463	193,997	194,530	194,937	195,343	195,750	195,900	196,050	196,200
CLASS 8 GARBAGE DIESEL EL. HYBRID	Fuel economy	MPDG	OEM	5.06	5.10	5.14	5.17	5.21	5.25	5.29	5.33	5.37	5.42	5.46	5.48	5.51	5.53
	Price	2017 $		231,600	230,733	229,901	229,104	228,342	227,813	227,316	226,849	226,286	225,753	225,247	224,512	223,804	223,121
CLASS 8 GARBAGE DIESEL HY. HYBRID	Fuel economy	MPDG	AFM	4.98	5.02	5.05	5.09	5.12	5.16	5.20	5.24	5.28	5.33	5.37	5.39	5.42	5.44
	Price	2017 $		226,600	226,933	227,265	227,598	227,930	228,463	228,997	229,530	229,937	230,343	230,750	230,900	231,050	231,200
CLASS 8 GARBAGE CNG	Fuel economy	MPDG	AFM	3.59	3.61	3.64	3.66	3.69	3.72	3.75	3.77	3.81	3.84	3.87	3.88	3.90	3.92
	Price	2017 $		246,600	246,933	247,265	247,598	247,930	248,463	248,997	249,530	249,937	250,343	250,750	250,900	251,050	251,200
CLASS 8 GARBAGE LNG	Fuel economy	MPDG	AFM	3.59	3.61	3.64	3.66	3.69	3.72	3.75	3.77	3.81	3.84	3.87	3.88	3.90	3.92
	Price	2017 $		256,600	256,933	257,265	257,598	257,930	258,463	258,997	259,530	259,937	260,343	260,750	260,900	261,050	261,200
URBAN TRANSIT DIESEL	Fuel economy	MPDG	OEM	3.42	3.45	3.47	3.50	3.52	3.56	3.60	3.64	3.67	3.71	3.75	3.77	3.78	3.80
	Price	2017 $		485,000	485,333	485,665	485,998	486,330	485,800	485,270	484,740	485,877	487,013	488,150	488,600	489,050	489,500
URBAN TRANSIT DIESEL EL HYBRID	Fuel economy	MPDG	AFM	4.55	4.58	4.62	4.65	4.68	4.73	4.78	4.83	4.89	4.94	4.99	5.01	5.03	5.05
	Price	2017 $		750,000	742,383	735,004	727,856	720,933	713,365	706,008	698,855	693,569	688,475	683,567	678,155	672,918	667,852
URBAN TRANSIT DIESEL HY. HYBRID	Fuel economy	MPDG	AFM	4.28	4.31	4.34	4.37	4.40	4.45	4.50	4.54	4.59	4.64	4.69	4.71	4.73	4.75
	Price	2017 $		535,000	535,333	535,665	535,998	536,330	535,800	535,270	534,740	535,877	537,013	538,150	538,600	539,050	539,500

	Attribute	unit	type	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
URBAN TRANSIT CNG	Fuel economy	MPDG	AFM	2.91	2.93	2.95	2.97	2.99	3.02	3.06	3.09	3.12	3.15	3.19	3.20	3.22	3.23
	Price	2017 $		530,000	530,333	530,665	530,998	531,330	530,800	530,270	529,740	530,877	532,013	533,150	533,600	534,050	534,500
URBAN TRANSIT BEV	Fuel economy	MPKWH	OEM	0.250	0.251	0.251	0.252	0.252	0.253	0.253	0.254	0.254	0.255	0.255	0.256	0.256	0.257
	Price	2017 $		800,000	794,033	788,191	782,473	776,876	770,535	764,310	758,200	753,867	749,644	745,528	740,830	736,236	731,742
URBAN TRANSIT FCEV	Fuel economy	MPKGH2	OEM					5.16	5.17	5.18	5.19	5.20	5.21	5.22	5.23	5.24	5.25
	Price	2017 $						986,330	975,800	965,470	955,336	947,061	938,974	931,071	922,663	914,432	906,374
SHUTTLE BUS GASOLINE	Fuel economy	MPGG	OEM	6.9	7.09	7.28	7.47	7.66	7.81	7.95	8.10	8.19	8.29	8.38	8.45	8.51	8.58
	Price	2017 $		76,400	76,690	76,980	77,270	77,560	77,847	78,133	78,420	78,603	78,787	78,970	79,047	79,123	79,200
SHUTTLE BUS DIESEL	Fuel economy	MPDG	OEM	8.63	8.87	9.11	9.34	9.58	9.85	10.11	10.38	10.53	10.67	10.82	10.90	10.98	11.06
	Price	2017 $		84,300	84,590	84,880	85,170	85,460	85,747	86,033	86,320	86,503	86,687	86,870	86,963	87,057	87,150
SHUTTLE BUS E85	Fuel economy	MPGE	OEM	4.97	5.10	5.24	5.38	5.52	5.62	5.73	5.83	5.90	5.97	6.03	6.08	6.13	6.18
	Price	2017 $		76,400	76,690	76,980	77,270	77,560	77,847	78,133	78,420	78,603	78,787	78,970	79,047	79,123	79,200
SHUTTLE BUS CNG	Fuel economy	MPGGE	AFM	6.56	6.74	6.92	7.10	7.28	7.42	7.56	7.70	7.78	7.87	7.96	8.02	8.09	8.15
	Price	2017 $		88,900	89,190	89,480	89,770	90,060	90,347	90,633	90,920	91,103	91,287	91,470	91,547	91,623	91,700
SHUTTLE BUS DIESEL HYD. HYBRID	Fuel economy	MPGP	AFM	10.53	10.82	11.11	11.40	11.69	12.01	12.34	12.66	12.84	13.02	13.20	13.30	13.40	13.49
	Price	2017 $		108,300	108,590	108,880	109,170	109,460	109,747	110,033	110,320	110,503	110,687	110,870	110,963	111,057	111,150
SHUTTLE BUS BEV	Fuel economy	MPKWH	OEM	1.050	1.061	1.071	1.082	1.093	1.104	1.115	1.126	1.137	1.148	1.160	1.171	1.183	1.195
	Price	2017 $		824,500	817,308	810,302	803,479	796,831	789,493	782,320	775,309	770,121	765,085	760,197	754,766	749,475	744,319
SCHOOL BUS GASOLINE	Fuel economy	MPGG	OEM	6.25	6.42	6.60	6.77	6.94	7.05	7.17	7.28	7.39	7.51	7.62	7.63	7.64	7.65
	Price	2017 $		89,300	89,588	89,875	90,163	90,450	90,770	91,090	91,410	91,630	91,850	92,070	92,213	92,357	92,500
SCHOOL BUS DIESEL	Fuel economy	MPDG	OEM	7.81	8.87	9.11	9.34	9.58	9.85	10.11	10.38	10.53	10.67	10.82	10.90	10.98	11.06
	Price	2017 $		97,300	97,588	97,875	98,163	98,450	98,770	99,090	99,410	99,630	99,850	100,070	100,213	100,357	100,500
SCHOOL BUS BEV	Fuel economy	MPKWH	OEM	0.904	0.913	0.922	0.931	0.941	0.950	0.960	0.969	0.979	0.989	0.999	1.009	1.019	1.029
	Price	2017 $		124,300	123,538	122,807	122,106	121,435	120,826	120,244	119,689	119,061	118,458	117,880	117,249	116,641	116,056
SCHOOL BUS CNG	Fuel economy	MPGGE	AFM	5.94	6.10	6.27	6.43	6.59	6.70	6.81	6.92	7.02	7.13	7.24	7.25	7.26	7.27
	Price	2017 $		109,300	109,588	109,875	110,163	110,450	110,770	111,090	111,410	111,630	111,850	112,070	112,213	112,357	112,500
SCHOOL BUS LPG	Fuel economy	MPGP	AFM	4.74	4.87	5.00	5.13	5.26	5.35	5.43	5.52	5.60	5.69	5.78	5.78	5.79	5.80
	Price	2017 $		107,300	117,588	117,875	118,163	118,450	118,770	119,090	119,410	119,630	119,850	120,070	120,213	120,357	120,500
MOTOR COACH DIESEL	Fuel economy	MPDG	OEM	6.96	7.15	7.34	7.53	7.72	7.87	8.01	8.16	8.26	8.36	8.47	8.49	8.52	8.55
	Price	2017 $		350,000	351,284	352,567	353,851	355,134	356,102	357,069	358,037	358,770	359,502	360,235	360,323	360,412	360,500
MOTOR COACH CNG	Fuel economy	MPDGE	OEM	5.91	6.07	6.24	6.40	6.56	6.69	6.81	6.94	7.02	7.11	7.20	7.22	7.24	7.27
	Price	2017 $		385,000	386,284	387,567	388,851	390,134	391,102	392,069	393,037	393,770	394,502	395,235	395,323	395,412	395,500

LIST OF ACRONYMS

A	Area
AMT	Automated manual transmission
APU	Auxiliary power unit
ATI	Automatic tire inflation
CAFE	Corporate average fuel economy
CARB	California Air Resources Board
C_d	Coefficient of drag
Energy Commission	California Energy Commission
CNG	Compressed natural gas
CO_2	Carbon dioxide, a greenhouse gas
DOE	United States Department of Energy
E85	A blend of 15 percent gasoline and 85 percent ethanol used to fuel dedicated ethanol powered vehicles and flex-fuel vehicles
EGR	Exhaust gas recirculation
U.S. EPA	United States Environmental Protection Agency
EU	European Union
GHG	Greenhouse gas
GVW	Gross vehicle weight
GVWR	Gross vehicle weight rating
HDS	H-D Systems
HHDT	Heavy-heavy duty truck
HVAC	Heating, ventilation, and air conditioning
IEPR	*Integrated Energy Policy Report*
kg	Kilogram
kW	Kilowatt, a unit of power
kWh	Kilowatt-hour, a unit of energy
LHD	Light-heavy duty (truck)
LNG	Liquefied natural gas
MDT	Medium-duty truck

MHD	Medium-heavy-duty (truck)
MPDG	Miles per diesel gallon
MPDGE	Miles per diesel gallon equivalent
MPEG	Miles per E85 gallon
MPG	Miles per gallon
MPGG	Miles per gasoline gallon
MPGGE	Miles per gasoline gallon equivalent
MPH	Miles per hour
MPKGH2	Miles per kilogram of hydrogen
MPKWH	Miles per kilowatt-hour
MPGP	Miles per gallon of propane
NHTSA	National Highway Traffic Safety Administration
NO_X	Nitrogen oxide
OEM	Original equipment manufacturer
PCCI	Premixed charge compression ignition
PM	Particulate matter
RIA	Regulatory Impact Assessment
SCR	Selective catalytic reformer
SwRI	Southwest Research Institute
TIUS	Truck Inventory and Use Survey
TPM	Tire-pressure monitoring
V10	Internal combustion engine with 10 cylinders
V8	Internal combustion engine with 8 cylinders
VIUS	Vehicle Inventory and Use Survey
WBS	Wide-base singles
WHR	Waste heat recovery

ATTACHMENT I:
H-D Systems (EEA) Report to Department Of Energy on Heavy-Duty Truck Fuel Economy

ENERGY AND ENVIRONMENTAL ANALYSIS, INC.

TECHNOLOGICAL POTENTIAL TO REDUCE HEAVY-DUTY TRUCK FUEL CONSUMPTION TO 2025

REVISED FINAL REPORT

PREPARED FOR:

U. S. DEPARTMENT OF ENERGY

UNDER SUBCONTRACT NO.4000106324
UT-BATELLE LLC
OAK RIDGE NATIONAL LABORATORY

PREPARED BY:

H-D SYTEMS
WASHINGTON DC 20016

DECEMBER, 2011

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1 INTRODUCTION

While there has been considerable attention paid to the costs and benefits of reducing fuel consumption and greenhouse gases from light-duty vehicles, heavy-duty commercial vehicles have received much less attention in spite of the fact that total fuel consumption is a significant and growing part of total transportation related fuel consumption. Some of this lack of attention is due to the widespread belief that trucking is an efficient market for fuel economy technology since fuel cost is a significant component of total cost of truck operation, and the commercial nature of the operation suggests that market inefficiencies will be resolved. However, discussions with truck fleet operators and truck manufacturers show that customers are unwilling to pay for technology that cannot demonstrate simple payback from fuel savings in about 3 years or less, which implies a steep discount on the value of lifetime fuel savings. This is partly due to the fact that new trucks are intensively used for the first 4 to 5 years of operation and then sold to second owners who use them much less intensively. Hence, the first owner usually expects to recapture the value of additional technology investment within the ownership period rather than expect some payback in the resale market. This report examines available technology to improve truck fuel efficiency and estimates their cost and benefit to develop a supply curve of fuel efficiency. The outcomes from different assumptions on the payback in terms of fuel savings allow a detailed computation of fuel savings and the cost of GHG reduction from the commercial truck sector.

Section 2 provides a summary of the characteristics of the existing fleet of heavy trucks, sub-divided into three classes based on the gross vehicle weight, termed light-heavy, medium-heavy and heavy-heavy. The data shows the use, annual mileage and fuel economy of each of these sub-classes and this type of data is used to gauge the applicability and benefit of different technologies to each sub-class. The data is from the 2002 VIUS which is relatively old but is unfortunately the only source of comprehensive data on truck use and real world fuel economy at the disaggregate level desired for this analysis. In addition, section 2 discusses the typical drive cycles over which fuel consumption should be evaluated. Trucks are used in a variety of applications ranging from long haul to vocational use. The lack of a fixed reference drive cycle by application is a major drawback in the analysis of fuel economy potential and this section makes a preliminary attempt to define specific drive cycles and the attendant energy losses for a number of different uses. These cycles and energy loss estimates form the basis for the technology benefit estimates over different applications. Since the completion of the draft of this report, the EPA and DOT have issued HDT fuel economy and GHG standards for 2014 and 2017, and have specified drive cycles for reference. The new drive cycles are compared to our findings in this report.

Section 3 provides a discussion of the available drive-train technology to improve fuel economy and most of this data was obtained from interviews of the staff of different heavy-duty engine manufacturers. The DOE's 21st Century Truck Program has sponsored a series of conferences on engine efficiency to assess the goal of attaining 50 percent thermal efficiency in the near term and 55 percent efficiency in the longer term for the diesel engine. Technologies identified to meet these goals were assessed for their potential to meet the goals at reasonable cost, and be brought to market in the time frame of interest. Based on engine manufacturer inputs, technologies were classified by cost and potential time frame of introduction.

Section 4 provides an analysis of technologies affecting aerodynamic drag, rolling resistance and weight reduction, i.e., body technologies. Many of these technologies have been available in the aftermarket for a long time but most have yet to attain significant market penetration. Our analysis focuses on the actual as opposed to claimed benefits and also examines potential negative attributes that may have contributed to the limited market penetration to date. In addition, our analysis focuses on the fact that many technologies' benefits are dependent on the baseline; for example, the benefits of many drag reducing technologies depends on the aerodynamic characteristics of the base truck and technology benefits cannot be treated as additive. This analysis creates a framework for examining marginal benefits based on the drag coefficient of current trucks versus the drag coefficient thought to be ultimately attainable.

Unlike the light-duty sector, fuel savings are also available from operational enhancements that range from reducing idle time to improved maintenance and driving practices. Operational strategies are not a focus of this effort but are summarized since many reports on truck fuel economy add these benefits to those attained by technology improvements, Data on these operational enhancements were largely derived from existing studies conducted by regulatory agencies such as the EPA, and the benefits and costs of these operational improvements are also included in section 5. One improvement is associated with idle reduction devices that fall between a pure vehicle technology enhancement and an operational enhancement, since the engine is often used to provide HVAC services for sleeper cabs overnight. This technology is considered in some detail in this report.

Section 6 documents the construction of the supply curves and the cost-benefit of technology in broad categories. The supply curves are developed by vehicle class, range of operation and body style for a total of 14 different truck sub-classes The analysis provides some insight into the future potential for fuel economy improvements under a free market and GHG based intervention scenario. One of the interesting findings of this analysis is that the potential maximum technology benefits in reducing fuel consumption are similar across most vehicle classes and use types but have very different cost and payback implications. The revised report also examines compliance with the new fuel economy standards and the expectation for real world fuel economy.

2 BASELINE DATA ON TRUCK CHARACTERISTICS AND OPERATIONS

2.1 OVERVIEW

The objective of this study is to develop estimates of the costs and benefits of a variety of fuel economy improvement options for the heavy-duty trucking sector in order to create a supply curve of fuel efficiency. This section provides an outline of the data that are used in the construction of this curve. This study considers technology-based fuel economy improvements as well as improvements in trucking operational efficiencies. The functional fleet-wide impact of the fuel economy improvement available from some of the technology options, and all of the operational options, are a function of both the per vehicle fuel economy potential of the option as well the operational characteristics of the fleet – that is, the portion of the fleet for which the option is applicable. This section presents data that are relevant for the entire fleet, and also documents the operational characteristics that are relevant for particular fuel efficiency improvements applicable to a sub-set of the trucking population.

Data for this study about the composition of the heavy-duty trucking vehicle fleet, and operational characteristics of vehicle use are drawn from the VIUS. The VIUS was conducted every five years from 1967 through 2002 (but suspended since). The VIUS data is from a survey conducted by the US Census Bureau that includes data on the physical and operating characteristics of the US truck population. The survey, the most recent version of which was collected in 2002/3, includes 98,682 observations with 453 variables on each truck.

The Motor Fuel Consumption model (MFCM) was used to estimate future fuel use and GHG emissions. The MFCM provides detailed projections of fuel demand by fuel type and vehicle type, given detailed inputs on the fleet characteristics. In this sense, the MFCM is an accounting model and has no built-in econometric framework, so that its projections are directly connected to inputs with no intermediate processing involving assumptions on consumer behavior. This simplicity has been useful for examining the potential impact of changes in vehicle fleet or fuel characteristics. Since the MFCM outputs are so input driven, the inputs have been periodically revised. DOE has used the MFCM since the late 1970's to project on-highway fuel demand.

In this analysis, the heavy-duty truck segment is broken into three sub-categories – Light Heavy-Duty Trucks (LHDT), Medium Heavy-Duty Trucks (MHDT), and Heavy Heavy-Duty Trucks (HHDT) – in order to properly represent the technological and operational differences between the vehicles in each sub-category. LHDT, mostly large pickups and large cargo vans, share many components with vehicles in the light-duty vehicle sector and for this analysis include all vehicles in GVW classes 3, 4 and 5. These vehicles are generally operated about 27,000 ± 3000 miles per year, and a substantial fraction of the fleet is powered by gasoline engines (~50% in 2002). MHDT include a broad range of vehicle types (pickup and delivery, rough duty for construction and mining applications, municipal waste, fire and emergency, and city buses), the majority of which are used in local or regional operations. This category included GVW classes 6, 7 and 8A and trucks in this class are typically used 35,000 ± 3000 miles per year, and the fleet is over 90% diesel. Gasoline engines for this subclass were phased out in the 1990s. HHDT (GVW class 8B) dominate heavy trucking fuel demand and are comprised mostly of long-haul tractor trailers (70% of HHDT) along with some construction and mining trucks. The trucks are used for long haul applications and average 98,000 miles per year. These trucks have been 100% diesel powered for many decades. Due to the differences in the technological make up and operational characteristics of each of the heavy-duty trucking segments, each sub-class is considered separately in this analysis. Data at this level of aggregation is utilized in this report to estimate the applicability and cost-effectiveness of different technological options to reduce fuel consumption

The VIUS dataset includes a variable for GVW classification with 15 categories. These GVW categories were combined to create LHDT, MHDT and HHDT distinctions according to the following definition: LHDT covers vehicles in the 8,500 to 19,000 pounds GVW range, MHDT covers vehicles in the 19,001 to 50,000 pounds range and HHDT covers vehicles over 50,000 pounds GVW.

2.2 HEAVY-HEAVY DUTY TRUCK (HHDT) SEGMENT

HHDT dominate demand for highway diesel fuel. The MFCM projects that HHDT will account for 67% of total highway diesel demand in 2020. This is a modest decline in percentage terms from the share in 2007 of 72%; however it represents an absolute increase of 23%, with annual consumption increasing from 26.6 billion gallons to 32.7 billion gallons, over the period as shown in Figure 2-1.

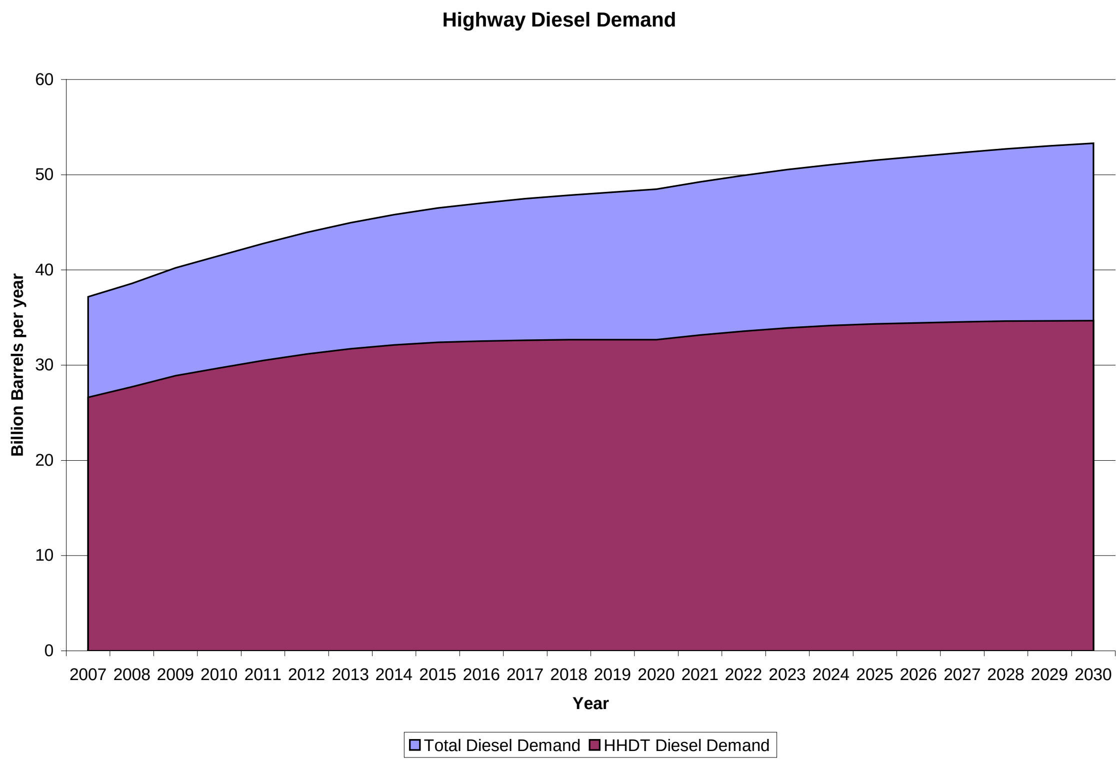


Figure 2-1: HHDT Diesel Demand

HHDT use is the greatest in the first 5 or 6 years of the vehicle lifetime, with annual mileage dropping steadily over the life of the vehicle. Figure 2-2 shows the decline in VMT by vehicle age for HHDT. The consideration of the operational characteristics of HHDT 5 years old or less is important because it represents the vehicle uses for the first-owners of HHDT – those that buy from the new vehicle market. Typically, trucks are used most heavily in their first 3 to 5 years, and are then sold into the secondary market. Efficiency improvements for new vehicles added to the fleet are chosen based on the operational characteristics of vehicles less than 5 years old, while efficiency improvements that are operational or retrofits apply to the entire existing fleet. While figure 2-2 shows that mileage decreases with age, over a third of all HHDTs travel over 75,000miles annually as shown in Figure 2-3.

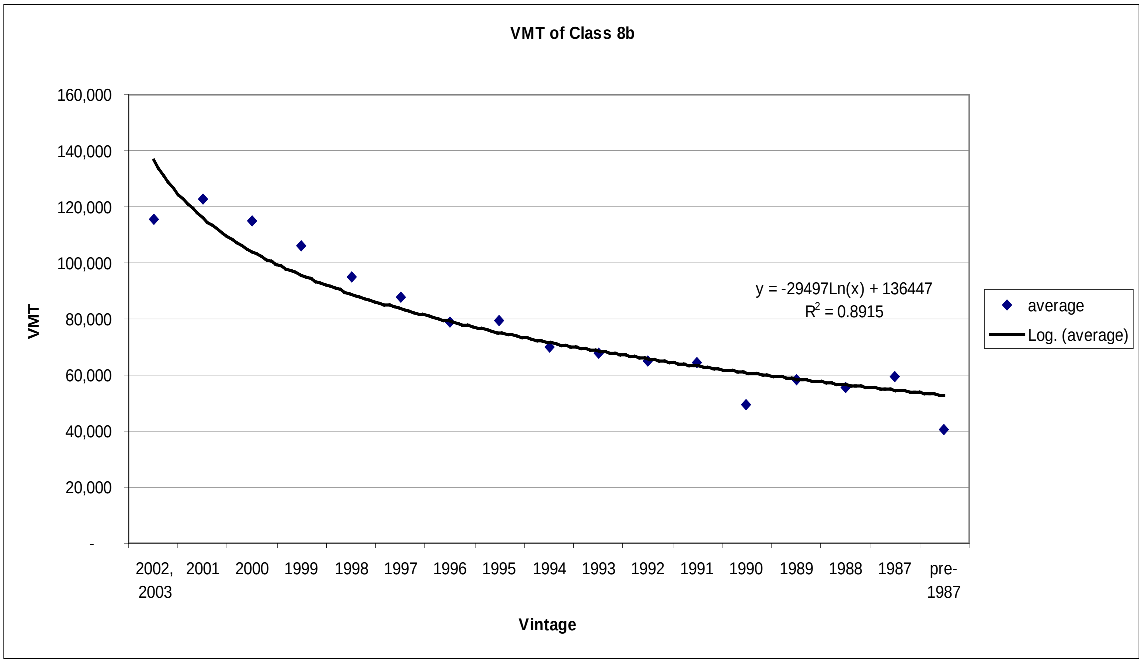


Figure 2-2: VMT by Vintage

Of all HHDT, 69% are tractors, rather than single unit vehicles. VIUS includes a survey question that asks respondents what percent of miles are driven with less than truckload service. This value is useful for calculating the population of vehicles for which fuel economy, on a per ton-mile basis, could be improved by changing government regulations limiting trailer length. 16% of miles, on average, are at less than truckload for tractor-style HHDT, leaving around 58% of total HHDT miles (69% times 84%) applicable for efficiency improvement from changes to trailer length limits.

Mileage is also characterized within VIUS according to the trip-length category in which mileage is accumulated. The largest portion of miles for all heavy-duty trucks up to Class 8A is in trips that are less than 50 miles per trip one-way. The HHDT category has trip length significantly shifted toward longer distance trips compared to the other heavy-duty subcategories as indicated in Figure 2-3. Almost 45% of all Class 8B trucks are used for trips whose length is over 200 miles, and this number is even higher for tractors with van body trailers. Off-road trip mileage is used to indicate vehicles for which advanced tires are not applicable because of the increased risk of tire damage, and for vehicles for which evolutionary improvements in the front-end aerodynamics are not applicable. Off-road miles are disproportionately distributed among HHDT – that is, most trucks have nearly zero off road mileage and the trucks that do make off road trips account for the majority share of total off-road mileage. The majority of total off-road mileage is accounted for by approximately the small percentage of HHDT that make a relatively high proportion of off-road trips – typically construction or mining vehicles.

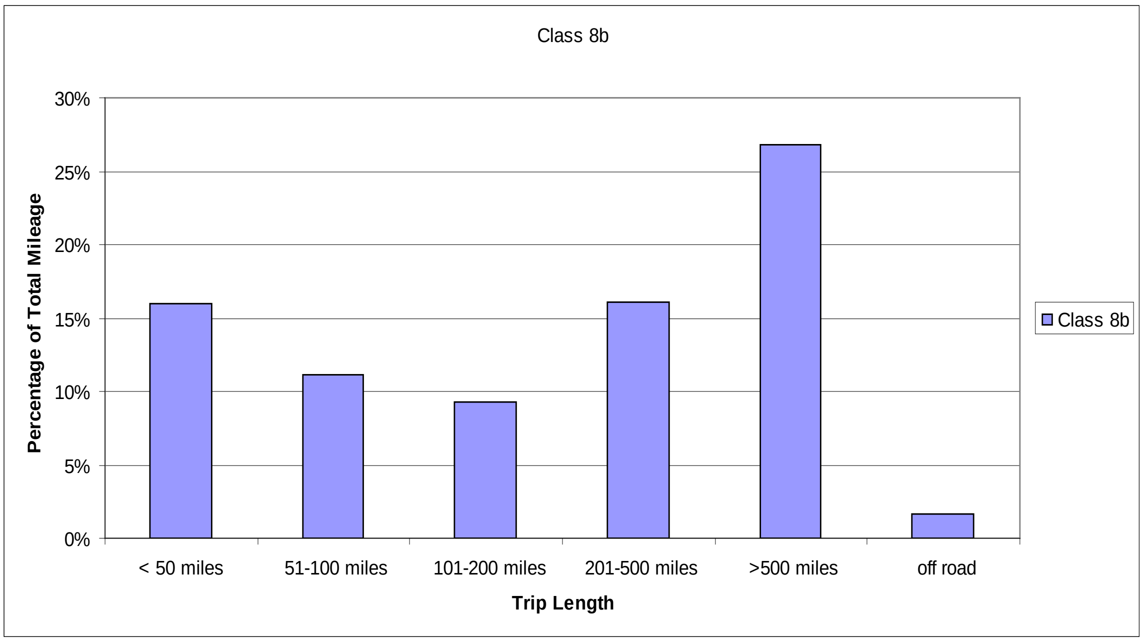


Figure 2-3: Mileage By Trip Length HHDT

For aerodynamic improvements that are related to the trailer, rather than to the front end of the vehicle (tractor related), the vehicle population is limited to HHDT that haul a van-style trailer. Of the entire HHDT fleet, approximately 42% haul a van style trailer while for younger vehicles (again, 5 years old or less) this figure rises to 63%.

Another opportunity for operational fuel savings is via driver training to educate drivers on how to optimize vehicle performance to minimize fuel use and costs. Fleet size is used as a metric of the applicability of this option to improve fuel economy – vehicles in small fleets are expected to benefit from driver training while drivers in large fleets (>20 tractors) usually already have a driver training program in place. The distribution of

HHDT population by fleet size (not including the vehicle surveyed) for both the entire fleet and for the fleet limited to vehicles 5 years old or less show that (summing the categories that are >20 tractors in a fleet) driving training can be applicable for 79% of the existing fleet and 61% of the new vehicle fleet.

Fuel economy by model year shows statistically significant increases over time. As of 2002, the year in which the VIUS data were collected, the average HHDT fuel economy was 5.86 miles per gallon with newer vehicles showing higher fuel economy. Vehicles 5 years or younger average 5.98 miles per gallon and the newest model year vehicles (2002/2003 in this survey) averaging almost 6.1mpg. Figure 2-4 shows the trend of fuel economy against vehicle vintage, and it should be noted that in this case that this is not an effect of truck age, but due to the fact that truck technology improves over time. The rate of improvement observed is about 0.5% per year for all Class 8B trucks but increases to about 0.7% per year for long haul use trucks over the 1987 to 2001 period. Anecdotal evidence suggests that about 0.4% to 0.45% was due to engine improvements and the vehicle improvements account for 0.25% to 0.3% per year on the long haul segment. Trucks used in rough duty applications or short haul appear to have much lower fuel economy gains of only about 0.25% per year, potentially only from engine improvements.

The fuel economy changes after 2001 have been measured by DOT in its comparative evaluation of rail versus truck efficiency, but the data is less reliable than VIUS data due to the much smaller sample size. The lower figure in Figure 2-4 shows that fuel economy actually declined from around 5.9 mpg attained in 2000/2001 to about 5.4 mpg in 2002, which is a decline of about 8.5%, associated with the phase-in of the NOx standard of 4 g.bhp-hr. The incorporation of urea-SCR systems in 2010 appear to have more than reversed the trend and the data shows newest trucks attaining 6.6 mpg. However, the data appears to exaggerate the effects of the NOX standards, and truck manufacturers suggest that the decline from the 4 and 2 g/bhp-hr standards were on the order of 5% which has

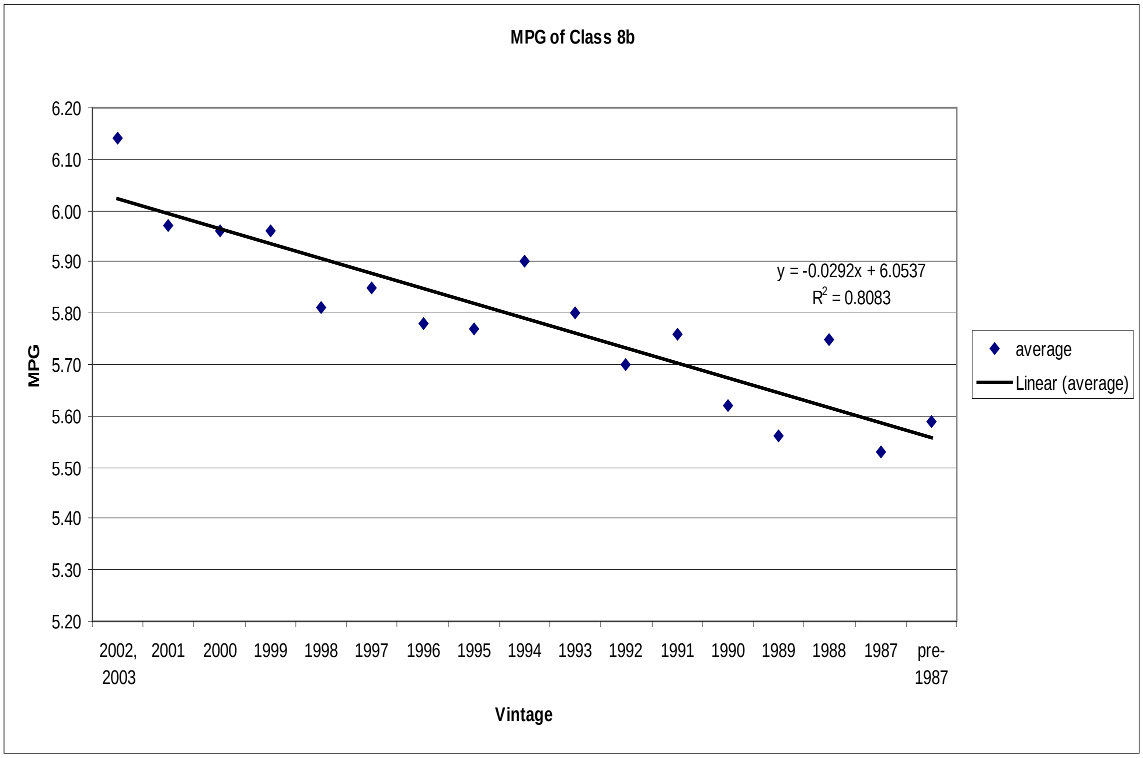
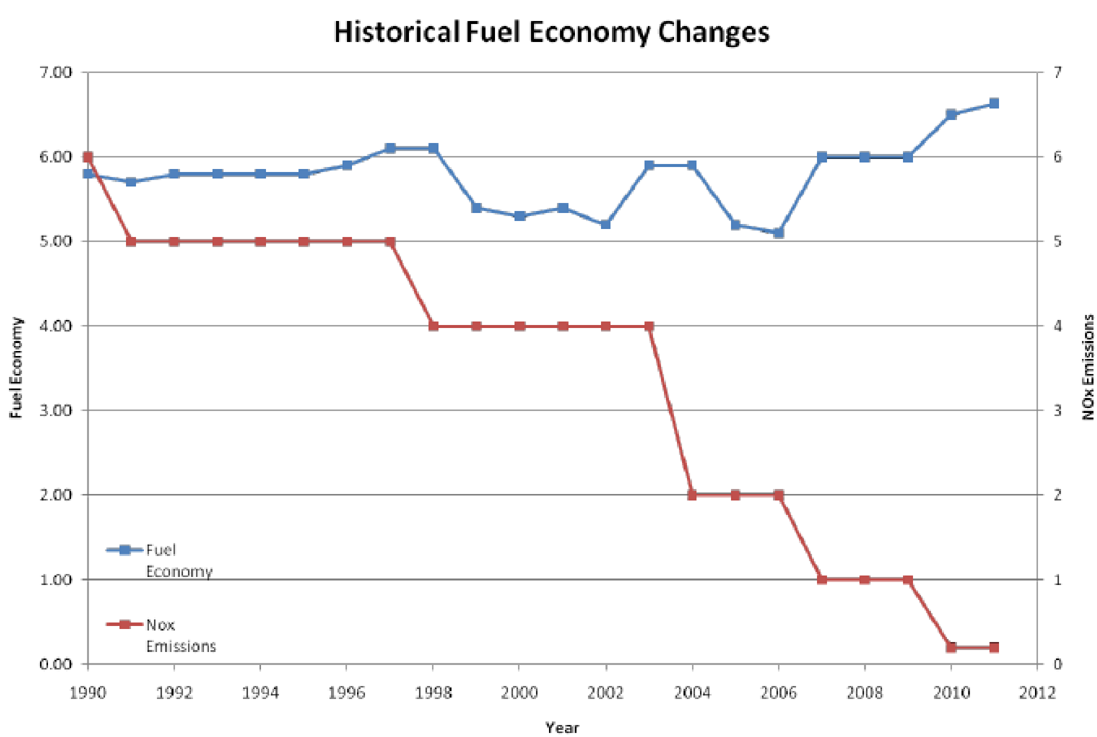


Figure 2-4: HHDT Fuel Economy by Vintage in 2002(above) from VIUS and in 2010(below)



been recovered by the urea-SCR so that new truck FE is about 6 mpg, which is similar to the level attained in 2000.

2.3 LIGHT-HEAVY AND MEDIUM-HEAVY SEGMENTS

Together, LHDT and MHDT account for over a quarter of total highway diesel demand, and this share is projected by the MFCM to increase modestly by 2030. MHDT engines tend to be around 7L to 10L displacement, varying across models by ±1.5L, while LHDT engines have a larger size range, with some domestic trucks having engines as large as 6L to 7L while some import truck models have engines as small as 3 or 4L. The LHDT population is more than double that of MHDT in the fleet, but LHDT consume only slightly more fuel on the whole (by around 12% in 2007) than MHDT as shown in Figure 2-5. As with HHDT, VMT per vehicle drops over time for LHDT and MHDT. Average LHDT mileage for the typical vehicle in the fleet is just over 25,000 annually, and for MHDT the average is just below 35,000 annually. However in the first five years of operation, the average annual mileage for LHDT and MHDT is over 20,000 and 45,000 miles, respectively a shown in Fig 2-6.

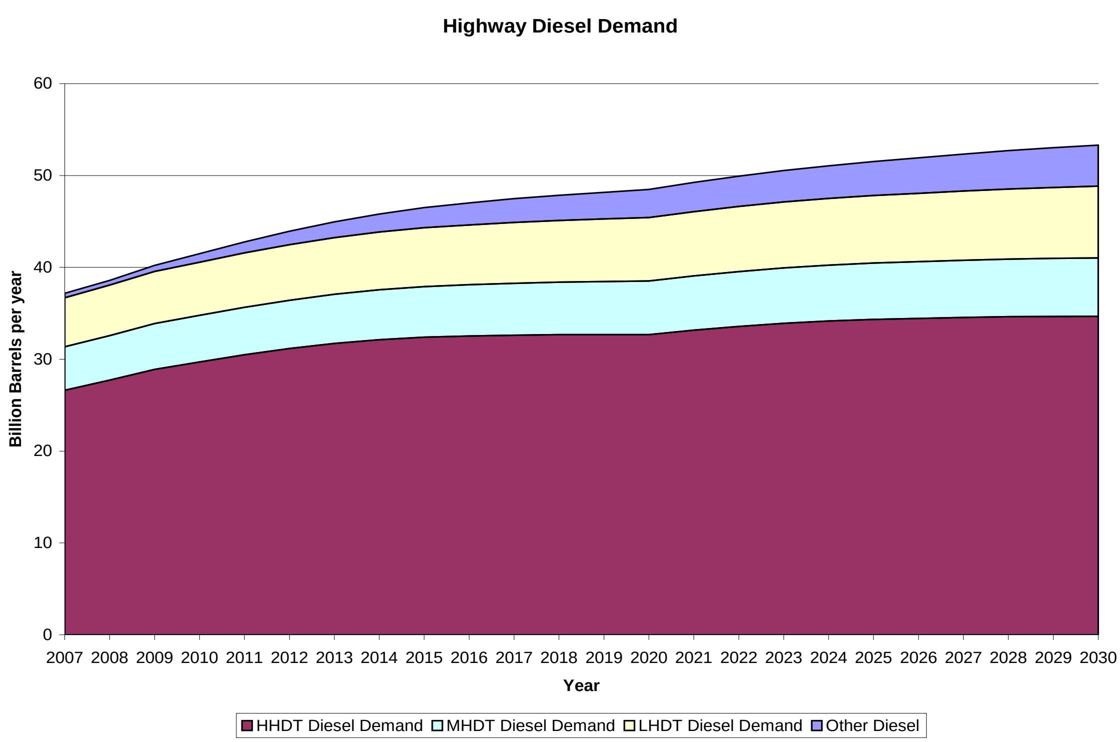


Figure 2-5: Highway Diesel Demand

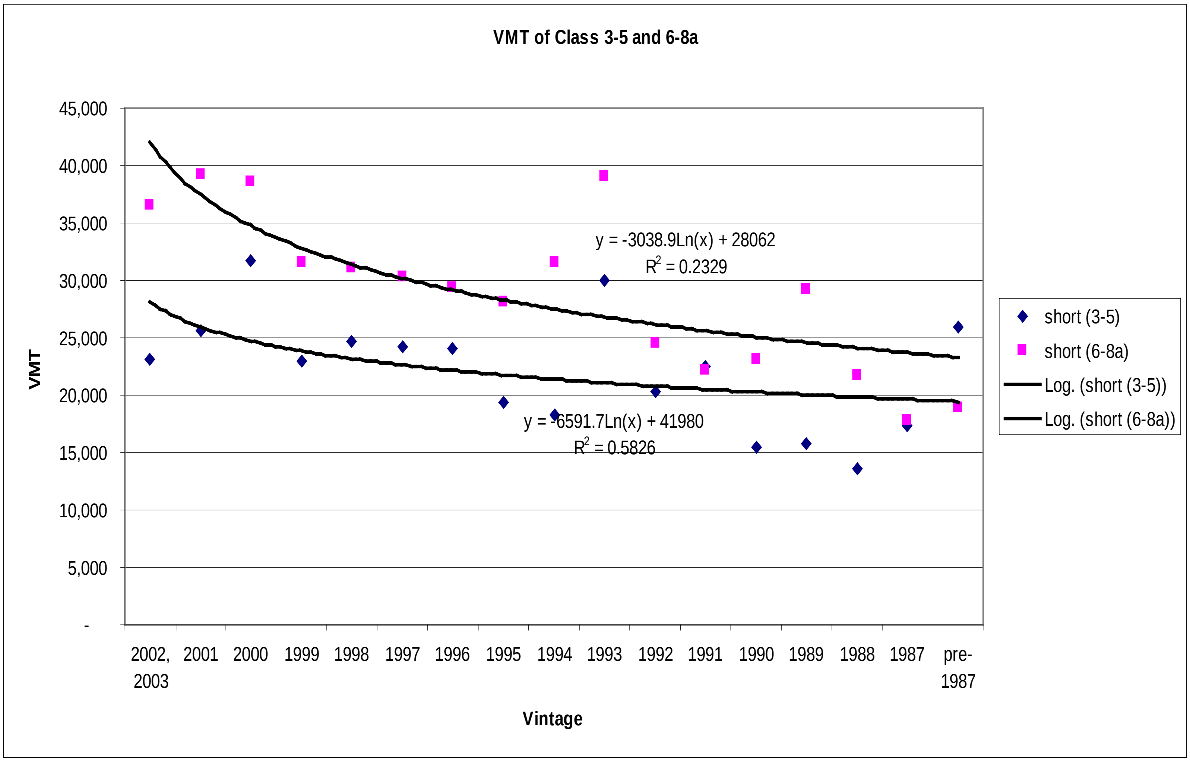


Figure 2-6 Annual Miles by Vintage and Class

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The distribution of mileage among the LHDT and MHDT subcategories is also much less variable than for the HHDT subcategory. Just over 10% of LHDT travel more than 30,000 miles annually, and fewer than 5% travel more than 50,000 miles annually. Similarly, just over 6% of MHDT travel more than 50,000 miles on an annual basis. On the other hand, over a third of MHDT travel less than 5,000 miles on an annual basis and over 70% of both LHDT and MHDT travel less than 20,000 miles annually, as shown in figure 2-7 below

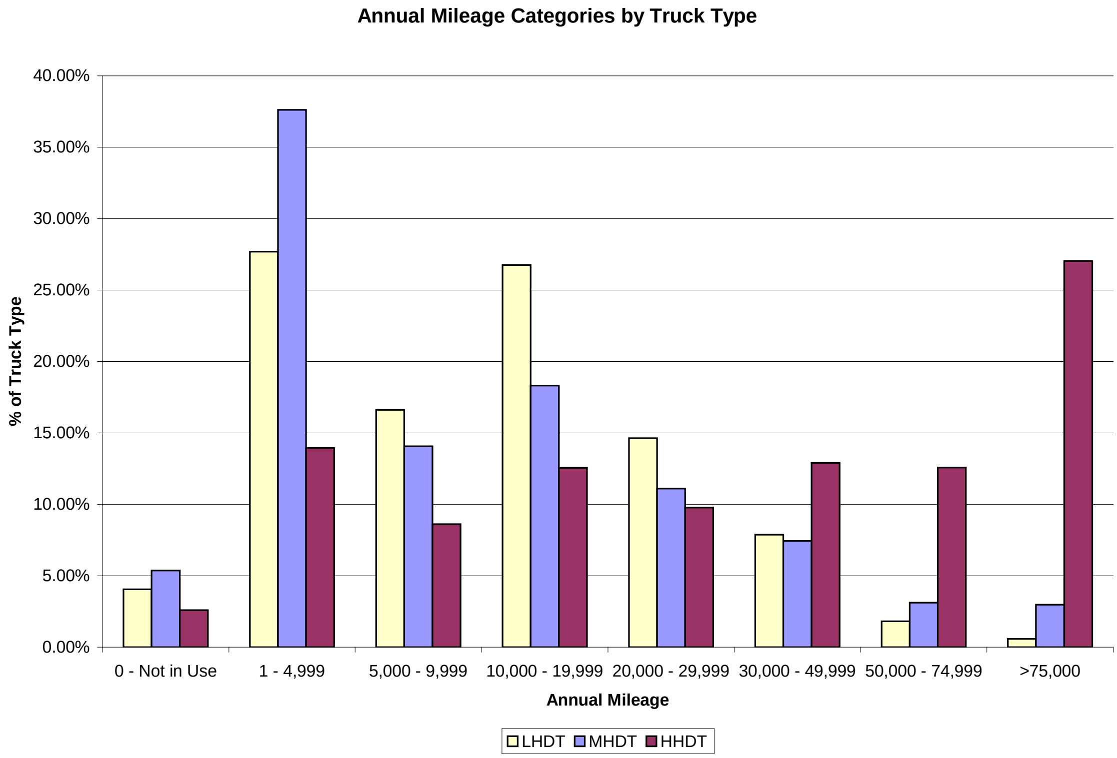


Figure 2-7 Annual Mileage Categories by Truck Type

Travel for LHDT and MHDT is skewed much more strongly to shorter trip lengths than HHDT. Around two-thirds of mileage for both LHDT and MHDT occurs on trips that are less than 50 miles. Less than 12% of mileage for both sub-categories is accumulated on trips over 200 miles.

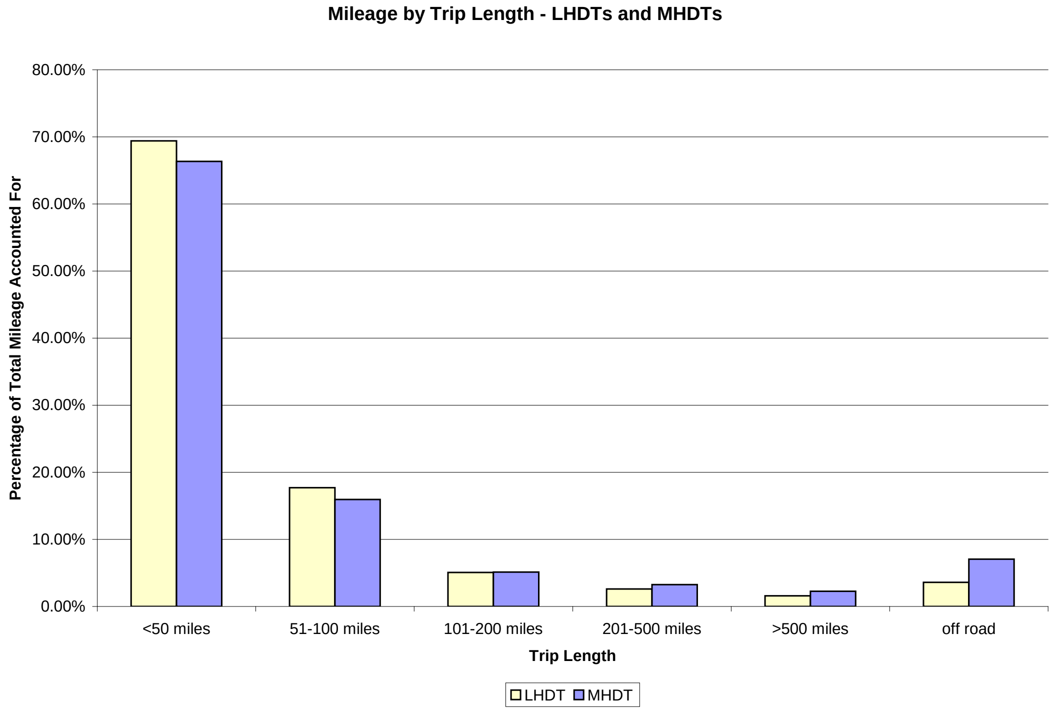


Figure 2-10 Mileage by Trip Length

Fuel economy has trended upwards over time, fairly consistently for the years delineated in the VIUS dataset, as shown in Figure 2-8. Average fuel economy for LHDT and MHDT vehicles, as of 2002 when the VIUS data was collected, is 11.2 and 7.9 mpg, respectively. For vehicles five years old and younger the values are 12.3 mpg for LHDT and 7.9 mpg for MHDT. The newest model year vehicles show fuel economy levels of 11.5 and 8.1 mpg respectively and fuel economy growth rates have been consistently in the 0.8 to 1.0 percent per year range over the time period examined. Fuel economy in the LHDT class grew very rapidly in the early 1990s when existing naturally aspirated and indirect injection engines were replaced by turbocharged direct injection engines with fuel economy jumping from 9.8 to 11+ mpg in that short period.

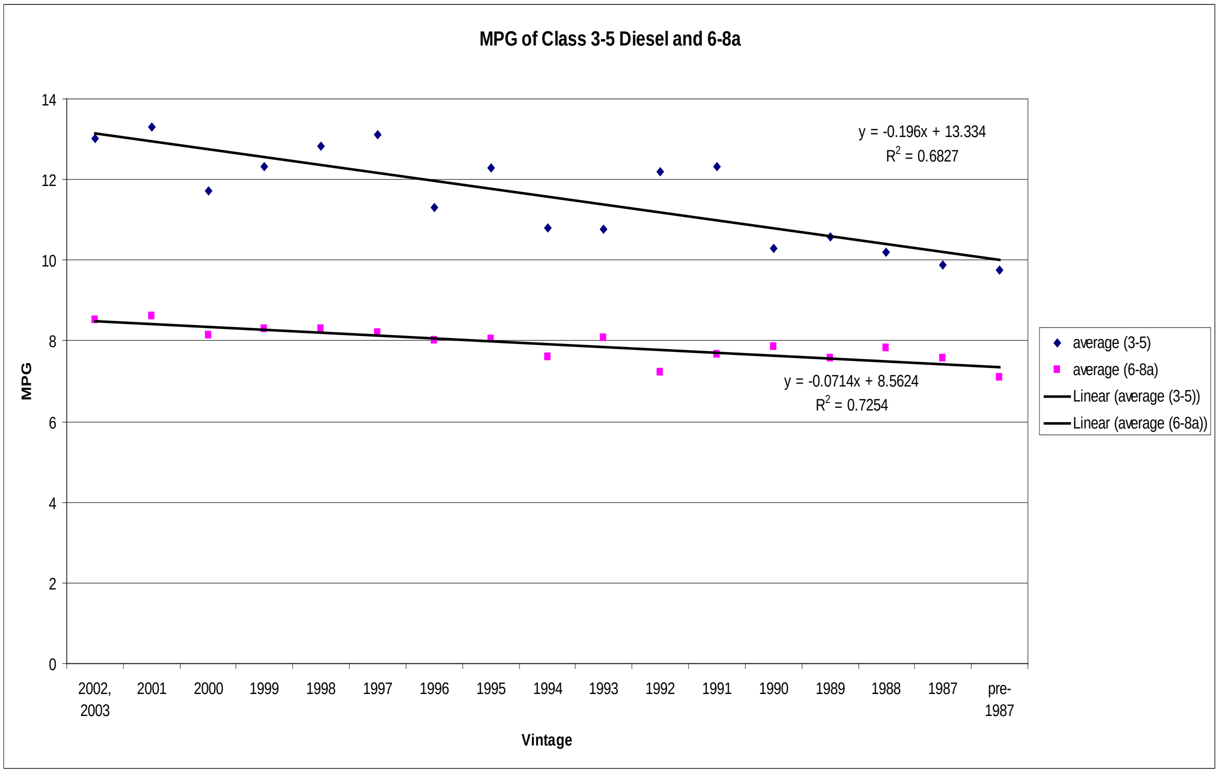


Figure 2-11 LHDT and MHDT Fuel Economy by Vintage

2.4 ENERGY CONSUMPTION ALLOCATION

The energy use by trucks has not been intensively studied as for light vehicles because there is no specific test cycle or driving cycle that is used as a reference. Since long haul trucks accumulate most of their mileage on the highway, some analyses have used a 65 mph constant speed case as a reference condition to allocate energy use to the different components, using analysis based on the first law of thermodynamics. In these analyses, the conversion of fuel energy by the diesel engine to shaft work is always the biggest user since the engine efficiency during driving is about 40%, implying that 60% of the energy is lost in this step. Other components of loss are much smaller, but this is misleading since it is the efficiency of the diesel engine which is approximately constant, not the absolute energy loss in fuel conversion, and a 10% reduction in shaft work results in a 10% reduction in fuel use. Figure 2-12 below is derived from DOE's 21st Century Truck Program for a constant speed 65 mph case.

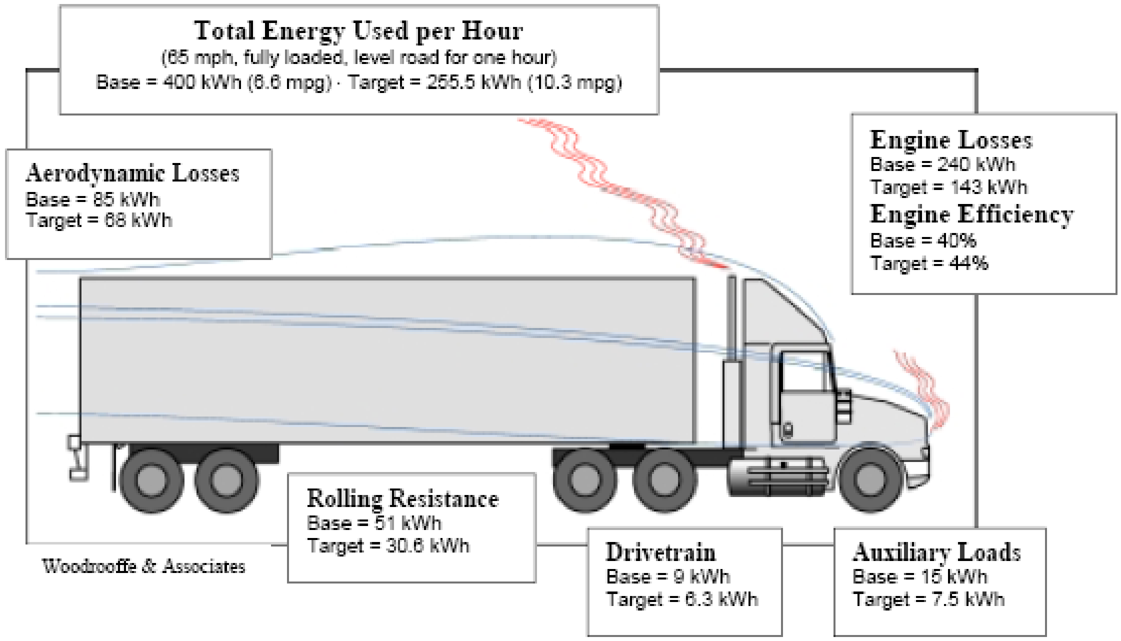


Figure 2-11: Allocation of Class 8B Truck Fuel Consumption at 65 mph.

In this case, base case engine output is 160 kW, with aerodynamic losses accounting for 85 kW or 53% of shaft work, tire rolling resistance for 51 kW or 32% of shaft work and the drive train friction loss and accessory drives accounting for 5.6% and 9.4% of shaft work. However, the constant speed condition is very unrealistic since rolling hills, road curves and traffic generally result in continuous speed and load variations as well as losses to the brakes. Steeper grades on mountainous geography have a very large effect but also affect the speed that trucks can maintain. Cummins provided a breakdown of shaft work on a "typical" long haul cycle in the Mid-west (i.e., modest road congestion and terrain effects) as shown in Figure 2-13, and this cycle uses 173 hp (129 kW) at an approximate average speed of 48 mph for class 8B truck.

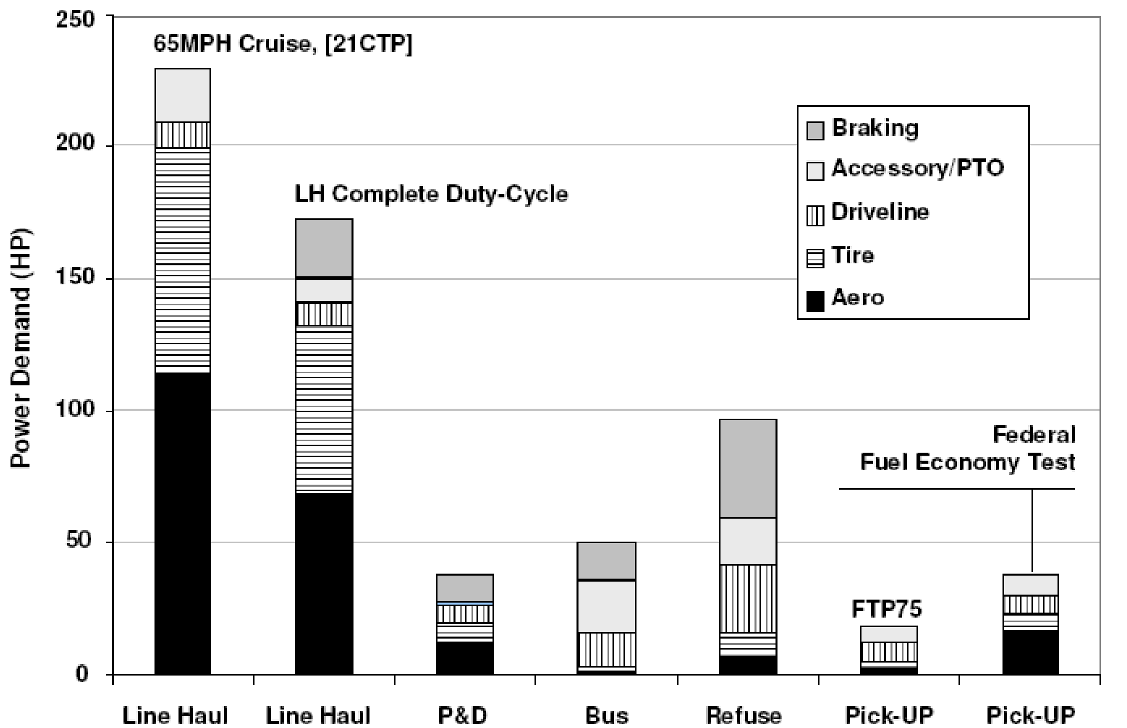


Figure 2-13: Power Demand for Typical Cycles on Heavy- Duty Trucks

The Cummins cycle shows a loss of 13 to 14% of shaft work to the brakes, with aerodynamic drag accounting for about 40% of shaft work, and rolling resistance accounting for about 37% of shaft work. Accessory drives account for 5% while driveline loss accounts for the remaining 4%. In this case, energy use is about 2.69 kWhr per mile as compared to 2.46 kWhr per mile in the constant speed 65mph case, which is 9% higher. In addition, idle fuel consumption is not accounted for in shaft work related analyses and is around 4 to 7 percent of total fuel for long haul trucks based on expert opinion (no hard data is available to estimate the idle fraction in real life). In vehicles with sleeper cabs, idle fuel consumption may be much higher if the engine runs all night to provide HVAC power for the cab. The Cummins cycle may underestimate actual brake losses since traffic congestion is much higher in the East and West Coast, while the topography in the mountain states may also result in larger braking energy loss.

In addition, fuel use at idle is not directly accounted for in analysis of tractive energy use and idle fuel use is not well documented or known. In some analyses of savings associated with idle reduction devices, EPA assumed that trucks idle 8 hours a day, 300 days a year for a total of 2400 hours per year. With fuel consumption at idle estimated at 0.8 to 0.9 gallons per hour, annual fuel use is about 2000 gallons which is 8 to 10 percent of total fuel use. These numbers appear very high from anecdotal information, and may be applicable only to the subset of trucks with sleeper cabs. In other HHDT applications, anecdotal information suggests that fuel use at idle may be only 2 to 4 percent of consumption, so that on aggregate, it is 4 to 6 percent of total fuel use as sleeper cab equipped vehicles account for about a third of all Class 8B trucks. Based on these estimates, we constructed energy and fuel use allocations as follows, to the nearest half percent

		Traction Energy	Fuel Use
Idle		0	5 ± 0.5
Inertia (lost to brakes)		13 ± 1	12.5 ± 1
Aerodynamics		40 ± 2	38 ± 2
Tire Rolling Resistance		37 ± 2	35 ± 2
Accessory Drives		6 ± 1	5.5 ± 0.5
Drive-train Loss		4 ± 1	4 ± 0.5

These allocations are utilized in the following sections to estimate Class 8B long haul truck related technology benefits. Allocations for other classes of trucks are more difficult because of the large variances in duty cycles. MHDT are used in suburban and short haul routes (less than 200 miles radius) for freight delivery, while many are used in urban pick-up and delivery, or by utilities (gas, electric, water, garbage). The “refuse” cycle shown in Figure 2-13 above shows average power of 95 hp (71kW) with 38% in inertia loss, 19% in accessory loads, 27% in driveline losses, 9% in tire loss and only 7% in aerodynamic drag loss. In general, MHDT have higher drive-train loss due to the relatively widespread use of automatic transmissions.

The Federal Test procedure for light duty vehicles has two drive cycles, one at 19 mph (city) and one at 48 mph (highway) with a weighted composite representing typical urban/suburban driving. The energy use for that cycle has been solved by numerical integration as a function of the drag to weight ratio and rolling resistance to weight ratio, and based on that solution we have derived the following values for fuel use fractions shown in Table 2-1:

		Line Haul (Manual Trans)	Regional Haul (Man. Trans.)	Urban/ Suburb. (Auto Trans)	Refuse/ Bus (Auto Trans)
Idle/ Decel.		5 ± 0.5	7 ± 0.5	8 ± 0.5	15 ± 1
Inertia (lost to brakes)		12.5 ± 1	31.5 ± 2	26.5 ± 2	32 ± 2
Aerodynamics		38 ± 2	25 ± 2	20 ± 2	6 ± 0.5
Tire Rolling Resistance		35 ± 2	25 ± 2	21.5 ± 2	8 ± 0.5
Accessory Drives		5.5 ± 0.5	7 ± 0.5	9 ± 0.5	16 ± 1
Drive-train Loss		4 ± 0.5	5.5 ± 1	15 ± 1	23 ± 1

2.5 REGULATORY CYCLES

The new regulations for HDT fuel economy announced in August 2011 incorporate drive cycles for fuel economy evaluation. However, the cycles incorporated appear to be relatively simplistic and quite general. The regulation requires separate testing of engines on the standard FTP and a simulation model approach for the entire vehicle.

The engine FTP cycle consists of 2 low speed cycles, the New York and Los Angeles non-freeway cycles, and one medium speed cycle called the Los Angeles freeway cycle. The cycle results are weighted to produce a near equal mileage on freeway and non-freeway operation which EPA recognized as not being representative of either “vocational” trucks or long haul trucks. Instead, three new cycles were selected. One was a new Transient cycle with an average speed of 15.3 mph and a distance of 2.84 miles, and includes almost 17% of the time at idle. The other 2 cycles are simply two constant speed modes at 55 mph and 65 mph, with no gradients or transients. The same three modes are applied to all trucks with different weightings. For sleeper cab equipped long haul trucks, the 65 mph constant speed mode is VMT weighted at 86% of operation while the 55 mph mode is weighted at 9%, with only the remaining 5% weighing for the transient cycle. For day cab equipped tractors, the weightings are 64%, 17% and 19% respectively. Even for vocational vehicles, the EPA assumes 37% of the VMT at 65 mph and 21% at 55 mph, with only 42% on the transient mode.

The analysis presented in Sections 2.3 and 2.4 show that the EPA assumptions of constant speed cruise at 55/65 mph are quite unrealistic, and essentially remove the role of inertia, while over-emphasizing the role of aerodynamic drag and tire rolling resistance. In addition, it is not clear if engine technology improvements will be fairly represented in the selected cycles as the benefit of some technologies such as turbo-compounding are better at constant high speed high load points on the engine map, and would provide a larger benefit on the test than in the real world.

3 ENGINE AND DRIVELINE TECHNOLOGY

3.1 BASELINE

Engines used in most heavy duty trucks over 10,000 pounds. GVW are powered by diesel engines, with all gasoline engines have essentially been phased out and only a few gasoline engines sold in the 10K to 14K GVW class trucks. Diesel engines have been historically classified as light heavy, medium heavy and heavy-heavy by the EPA with different durability requirements. In the light heavy class, engines were typically in the 6L to 9L displacement range; in the medium heavy class, the were in the 7L to 11L range and heavy-heavy trucks used engines over 11L. With the advent of common rail fuel injection systems and high pressure turbo-charging, engine specific output has increased significantly and the lines of distinction between classes are not as well defined.

In the light heavy class, the Cummins B-series 6.7L, the Navistar 6.4L and the GM 6.6L engines account for the vast majority of engines sold, with the Cummins 6 cylinder engine sold on Dodge trucks, the Navistar V8 engine on Ford trucks, and the GM V8 engine on Chevy/GMC trucks. In the medium duty sector, the Navistar DT 466 engine, the Cummins C series 8.3L engine and the Detroit Series 50 (now replaced by a Mercedes engine) are the most popular models. In the heavy-heavy category, the Cummins M series engine and the N series engine, the Caterpillar C13 and the DDC series 60 engine were the most popular. These engines have been updated or replaced for 2010 by the ISX13 and 15 engines from Cummins and the Mercedes 13L and 15L engines, while Caterpillar's on-highway engines have been discontinued and replaced by the "Maxxforce" 11 and 13 engines. The Mercedes 15L engines are the first turbo-compound engines sold in North America. In addition, many light heavy engines are used in medium duty applications, while the medium duty engines are now used in many of the lighter weight heavy-heavy applications.

In class 8 trucks, the vast majority (about 75%) use the 10 speed manual transmission, while only about 8% (mostly vocational trucks) use automatic transmissions. The remainder used manual transmissions with higher number of speeds, typically 12 or 16. This is consistent with the information in the VIUS which shows the heavy-heavy segment having 92.3% manual transmissions, 6 percent automatics and 1.7% automated manual transmissions. In medium duty trucks, the numbers are almost reversed with about 75 percent using six-speed automatic transmissions and 5 to 8 percent using the automated manual transmission (AMT). The VUIS data shows automatic penetration at 78.2% but has automated manual transmissions at only 0.7%, but AMT models have been newly introduced since 2002 and the information from manufacturers seems defensible. The remainder use 6 or 8 speed manual transmissions. At the light heavy end, almost 70 percent use automatic transmissions which were largely 4 –speed units in 2008 but are now transitioning to 6-speed units. The remaining 30 percent use 5 or 6 speed manual transmissions, and these numbers are confirmed in the VUIS data.

The efficiency of diesel engines over time has improved at slightly under 0.4% per year over the 1975 to 2003 period but has since decreased due to the imposition of strict Nox emission standards in 2004 of 2.5 g/bhp-hr, followed by the PM standards and the further tightening of the NOx standards in 2007 and 2010.

As shown in the figure 3-1 above, the peak efficiency point (right scale) of advanced heavy-duty diesels reached a maximum of about 44% but then declined to about 40%. In 2010, most heavy-heavy duty diesels will use exhaust after-treatment to control NOx that will allow engine-out emissions to increase relative to the 2007-2009 engines with efficiency increasing to 42%. The figure above also shows Volvo's hypothetical projection of efficiency at constant NOx emissions standards suggesting that fuel consumption has increased by 11% relative to this hypothetical level, but other manufacturers suggest that the loss may be only 5 to 6 percent, suggesting a peak efficiency of close to 45% at engine out NOx levels of 6g/ bhp-hr, a standard that has been in force since 1990. The historical rate of improvement estimated from the 38% efficiency level in 1980 to 44% in 2000 suggests engine thermal efficiency improvements on the order of 0.3% per year or a fuel economy improvement of 0.73% per year.

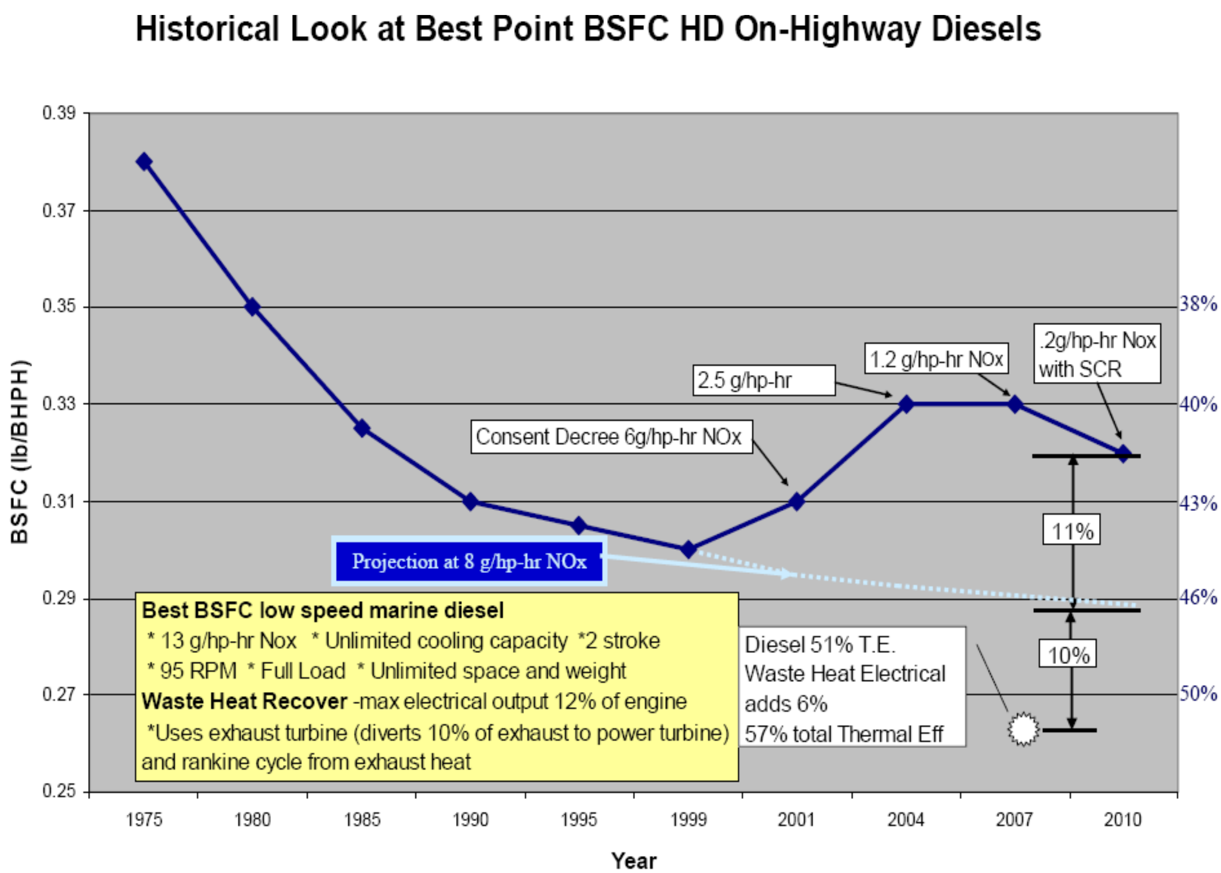


Figure 3-1

Source: Volvo

The 0.73% improvement per year is much higher than the 0.4 % to 0.45 % observed in the VIUS data described in Section 2 of this report, suggesting that some of the efficiency gains have been lost also to higher power ratings, and to time lags in the best technology being introduced in all engines. Another possible explanation is that peak efficiency attained in 2002 was on the order of 42 %, not the 45% shown in the figure, which would be consistent with an improvement of 0.45 % a year for 22 years. The rate of improvement is also not linear since the thermodynamic second law efficiency limit is an asymptote. Also, the above efficiency values are for heavy-heavy diesels and typically, the peak efficiency of the medium heavy diesels have been lower by about 1.5 to 2 %, and those of light-heavy diesels lower by about 2% to 3%, due partly to the smaller bore size which results in higher heat loss, and partly to the higher operating RPM which results in higher friction.

3.2 ENGINE IMPROVEMENT TARGETS AND ACTUAL POTENTIAL

Cummins provided a detailed map of energy flows for a recent model engine with a brake efficiency of 42%, as shown in Figure 3-2. Indicated efficiency of 50% is the current combustion duration limited diesel cycle efficiency, but with high EGR flow, there is more heat rejection to the coolant and EGR coolers than to exhaust. Heat rejection to exhaust has decreased from about 30 percent before the use of EGR (pre-2004) to 26 percent now, which has ramifications for the efficiency of heat recovery from turbo-compounding. Caterpillar data for a C15 engine with 42 percent efficiency shows exhaust gas heat rejection at 22 percent, but also shows heat loss from low pressure EGR (post Turbo) to be 5% for a total of 27% heat available after the turbo- charger. The heat loss values in figure 3-3 form the basis for Cummins' analysis of improving the brake efficiency to 52.5% in the future.

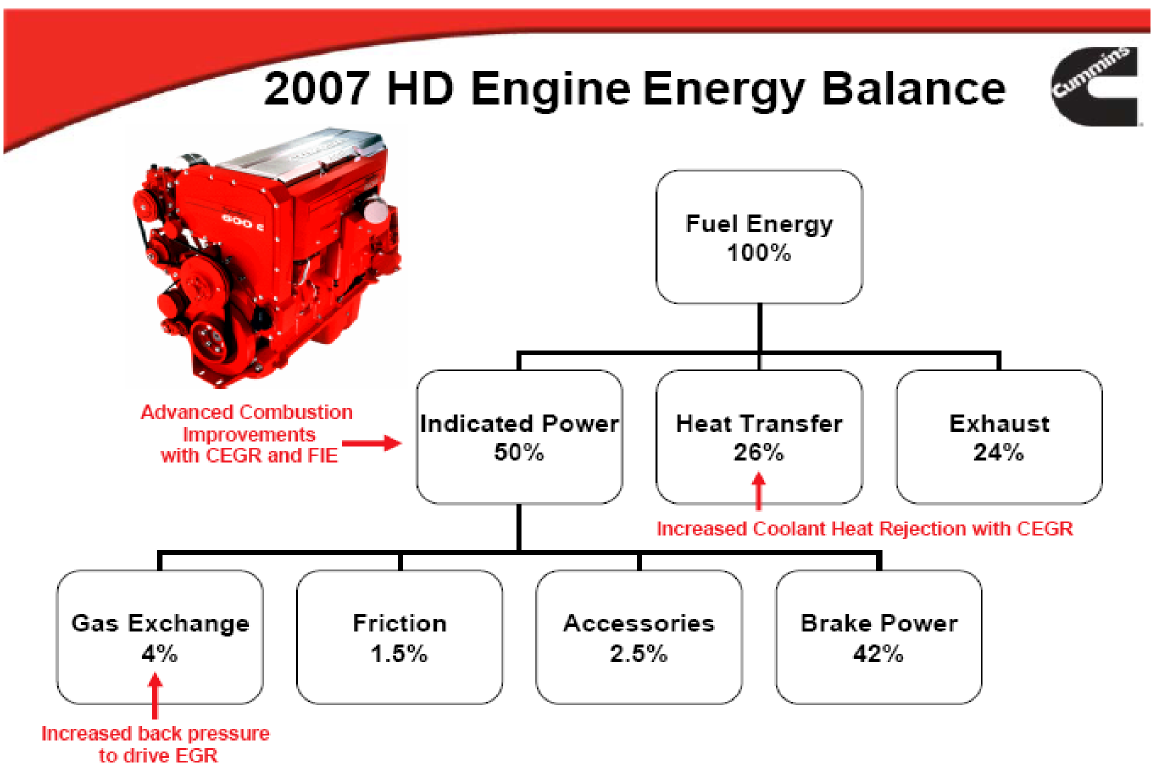


Figure 3-2: Distribution of Energy Losses in Current Engine

Figure 3-3 shows the energy flows modeled by Cummins to achieve the 52.5% efficiency target. This would require increasing indicated efficiency to 58%, while significantly reducing gas exchange losses indicating a fuel economy (FE) benefit of 25% (52.5/42-1). This would be the benefit for the base engine, and exhaust heat recovery could add another 6 to 8 percent fuel efficiency with advanced heat recovery systems, leading to a potential target figure of 31 to 33 percent FE improvement from the engine alone (engine total efficiency would be around 55%). Of course, the entire benefits of the target may not be attained in practice. If the historical FE improvement rate of about 0.45 % per year were to continue to 2030, engines would be 9.5% more fuel efficient by 2030 relative to 2010. Hence, there is a potential margin of 21% to 23% additional FE available from additional technology to meet the DOE engine efficiency targets. However, most manufacturers believe that such a large increase will not be possible and reaching 49% to 50% brake efficiency itself will be a major challenge,

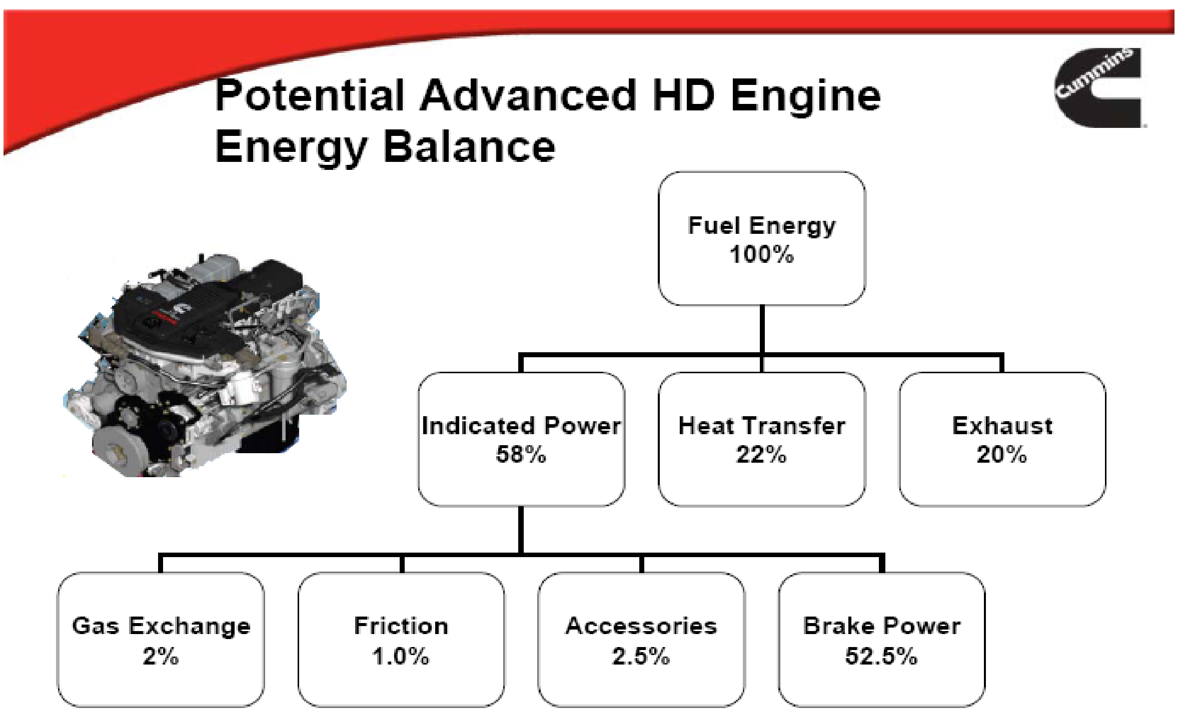


Figure 3-3: Estimated Distribution of Energy Loss in Advanced Engine

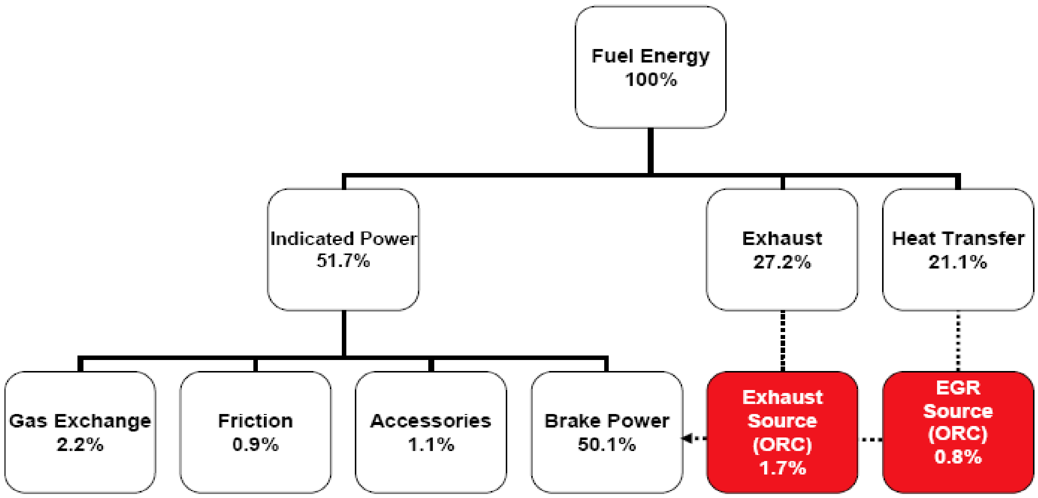


Figure 3-4: Actual potential by 2020 time frame

Source: Cummins

The DOE goals are to increase engine indicated efficiency to 58% by reducing heat transfer and exhaust heat energy loss. Brake efficiency is further enhanced by a 50% reduction in gas exchange losses, and a 33% percent reduction in friction loss, with accessory energy loss reduced by electrical drives included as a separate possibility with hybridization. Exhaust energy recovery through turbo-compounding and/or organic Rankine cycles can increase the overall brake thermal efficiency to about 55 % in constant high speed operation. Note that each 1% increase in efficiency increases FE by about 2.4%. The 55% efficiency path is a goal or target, and Cummins also provided a likely path towards a 50% goal that could be achieved over the next decade. As shown in Figure 3-4, the indicated efficiency increase is much more modest, and the 50% brake efficiency could be attained with an indicated efficiency of about 52%, with exhaust heat recovery. This path is consistent with the statements of other manufacturers about the potential to 2020 or 2025, implying a total increase of about 20 percent in fuel efficiency.

The specific technologies to improve indicated power to 50% include

- advanced common rail injection systems with very high injection pressure (2200 bar+)

- advanced injectors with multiple injections per stroke capability,
- advanced EGR cooling systems,
- closed loop injection control and
- improved air handling with an advanced twin sequential turbochargers or electrically assisted turbochargers.

3.3 COMBUSTION IMPROVEMENTS

Advanced injection systems and advanced injectors are likely to have a significant contribution to the overall improvement of efficiency at low engine-out Nox emissions. A very comprehensive analysis by Bosch shows the dependence of the injection pressure benefit to be a strong function of engine out Nox level. The 2010 emission standards require urea-SCR emission control systems that allow engine out Nox levels of 1.0 to 1.1 g/bhp-hr to attain the tailpipe standard of 0.2 g/ bhp-hr implying a catalyst system efficiency of around 85%. The engine out level translates to about 1.3 to 1.4 g/ kWh in European terms. As shown in the figure from Bosch below, the benefit of 2400 bar system over the typical 1800 bar system at this engine output is 3% at the “B50” operating point corresponding to 50 mph cruise on a highway. Increasing further to 3000 bar could enable an additional 1.5% fuel consumption benefit according to Bosch. These benefits continue to increase at even lower engine out Nox levels. In this context, engines operating at lighter average loads (as in trucks used for regional haul at lower speeds) will see smaller benefits from advanced injection systems.

It should be noted that the new Mercedes engine with turbo-compounding also features a hydraulically amplified CRS system from Bosch that currently operates at 2300 bar but is capable of 2500 bar. The next generation 3000 bar pressure systems would likely not enter the market until late in the next decade, possibly around 2018. Manufacturers confirm the benefits of increased pressure but suggest that a 2 percent benefit may be more reasonable as an average. The 2010 Navistar “Maxxforce” engines are being certified to a 0.5 g/ bhp-hr Nox standard without the use of urea-SCR catalyst systems.

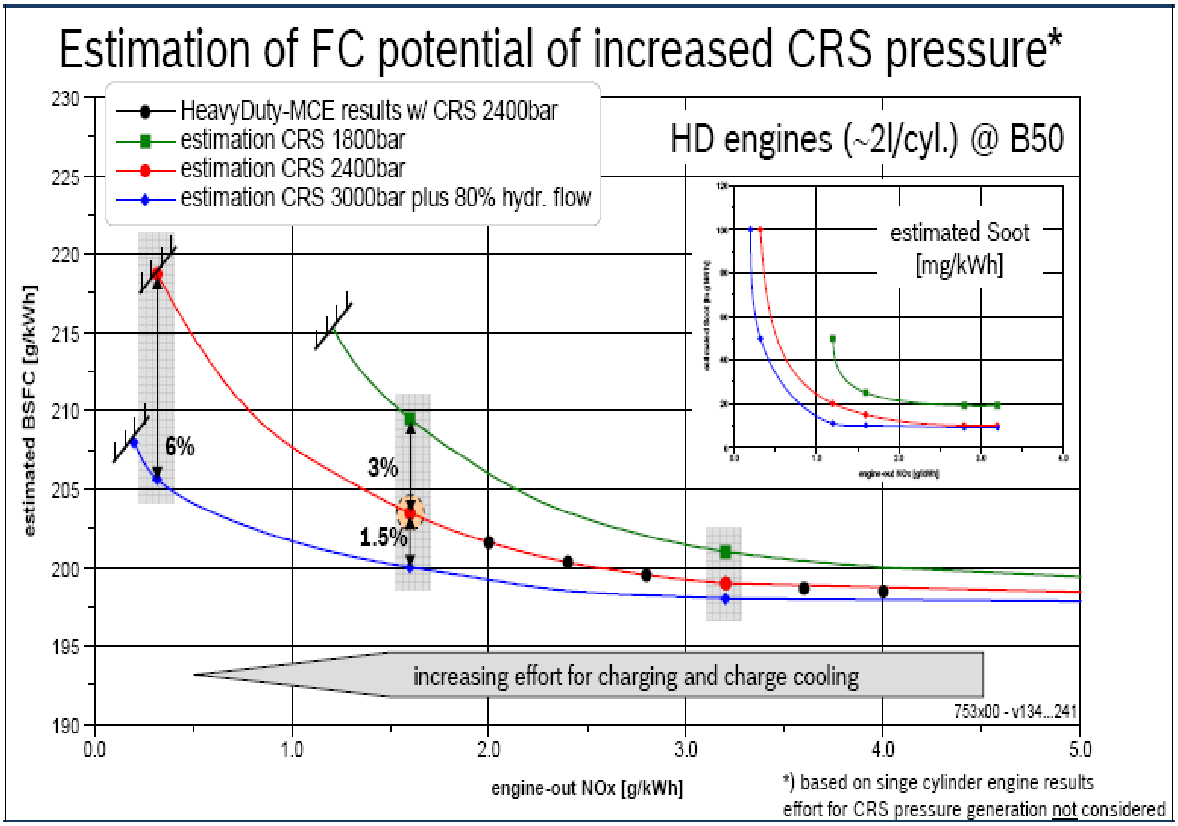
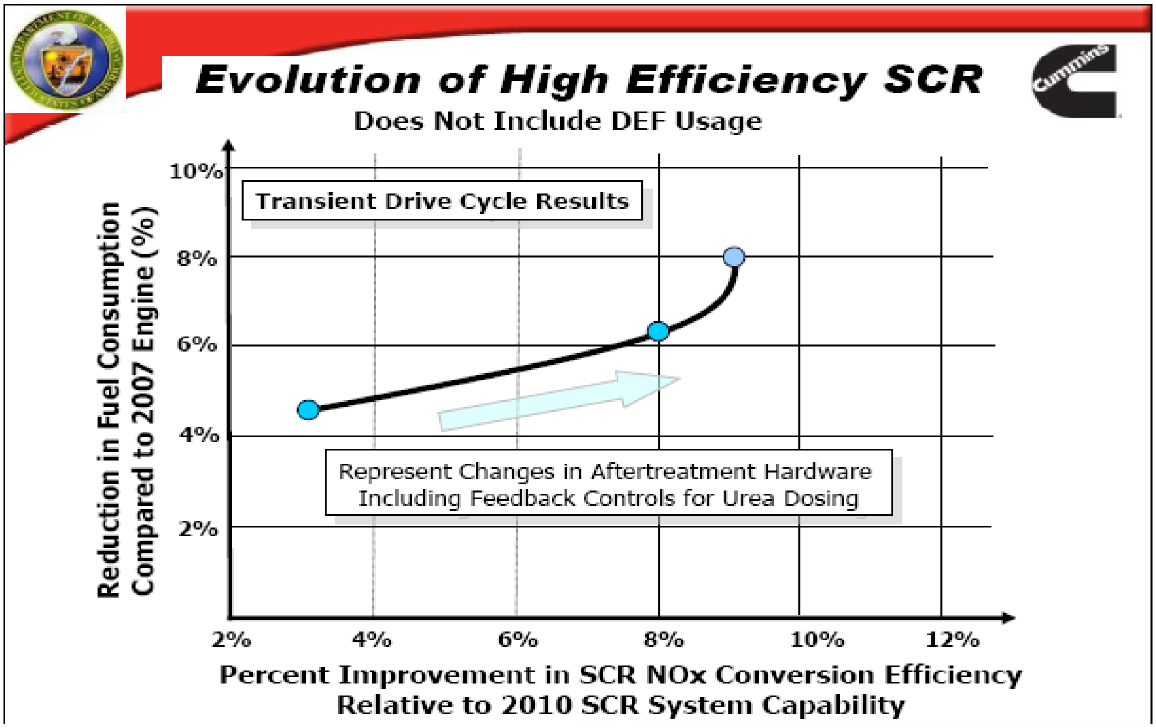


Figure 3-5: Effect of Common Rail System Pressure on BSFC

They utilize a 2200 bar system, and at this very low engine-out Nox level, the benefit of a 3000 bar system is assessed by Bosch at almost 6%. Manufacturers believe that the benefits could be around 4% to 5% after subtracting the energy used to increase rail pressure, but it is not clear if Navistar will continue to use a non-catalytic approach to meet the 0.2 standard. Moving to the urea- SCR system allows some recovery of efficiency to a level of 43% to 43.5%, which would improve fuel economy by 2.5% to 3%. However, the systems need to be filled with urea (sometimes referred to diesel exhaust fluid) which is consumed at a rate equivalent to 2 to 3 percent of fuel consumption. This level of FE improvement in 2010 has been confirmed by several engine manufacturers, while Cummins shows an improvement of 4+ % below. However, the cost of urea is a major concern, and the higher fuel cost of an in-cylinder Nox control system may be more than offset by the reduction in cost from not having to refill the urea system. The 2500 bar fuel injection system cost adds about $1500 to retail price over a 2000 bar system, while the 3000 bar system may add $2500 relative to current systems.



The current **urea SCR systems** operate at about 80 to 85% cycle efficiency and further improvement to 90+% is possible over the next five to eight years. This would allow engine out Nox levels to increase to almost 2 g/bhp-hr at constant tailpipe standards allowing another 1% efficiency increase or a 2.5% fuel economy increase, corresponding to a urea-SCR system efficiency increase of about 6 percent in the Figure 3-6. We anticipate that this improvement will be due to learning and incremental technology improvements but will not add additional cost to the system.

The **sequential twin turbocharger** concept has been introduced by several manufacturers such as Navistar for 2010, and constitutes one form of waste heat recovery. The twin turbo concept with inter-cooling between stages allows faster throttle response and more uniform boost capability over the RPM range. The twin turbo concept allows the engine to be downsized by 10 to 12 percent and still provide adequate low RPM torque and drivability at low speeds. This level of engine downsizing has occurred over the last 15 years, with the typical engine size for a 80,000 pounds. GVW vehicle and a 425 HP rating decreasing from around 15L to 12.5L to 13L. It is not clear if further downsizing will occur in the market in the near term, but additional downsizing to 11L to

11.5L is likely in the 2017 to 2025 time frame. DDC reported that improvement in turbocharger compressor and turbine efficiencies could provide a 1% to 1.5% FE benefit in the near term. The twin turbo approach has been used with engines certifying at very low engine-out Nox levels, with the high EGR rate making high boost a requirement to provide enough air for combustion. We estimate that the twin turbo concept with further downsizing to provide a 2.5 % to 3 % benefit in fuel economy by 2025. The twin turbo system adds about $1200 to engine price relative to a single turbo system with the same HP rating (i.e. a larger displacement engine)

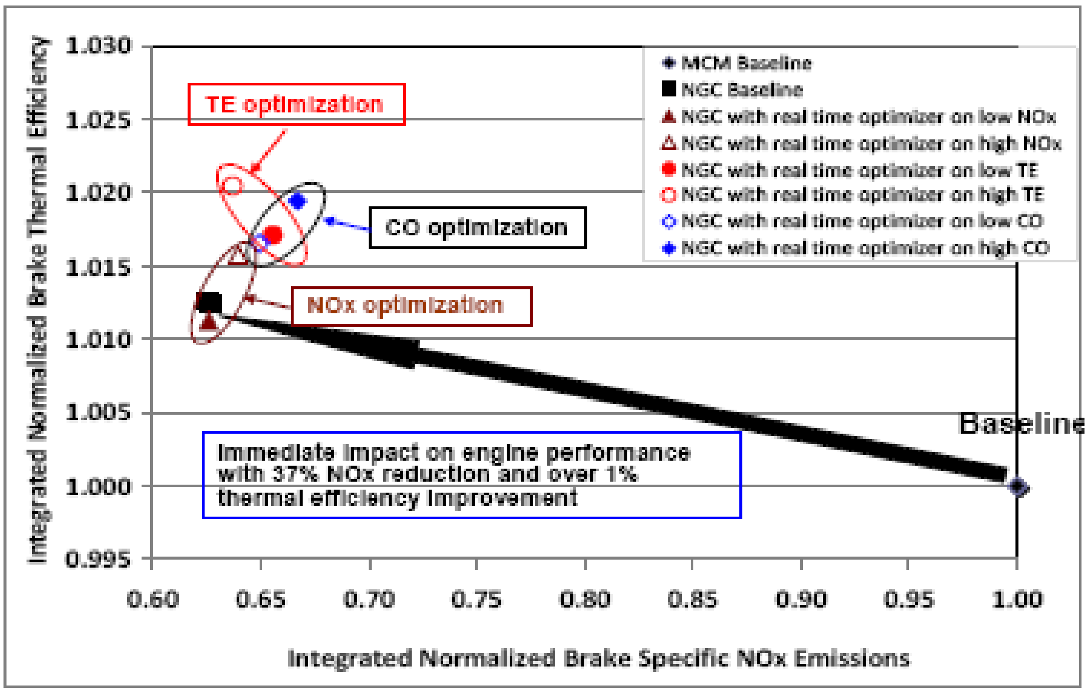


Figure 3-7: Benefits of Closed Loop Combustion Control

Closed loop combustion control has always been seen as a major goal to simultaneously improve emission and fuel economy performance. The new flexible fuel injection systems with amplified common rail and advanced injectors capable of multiple injections can allow PCCI combustion especially at lighter loads up to 10 bar BMEP. This would be more helpful on medium duty diesel engines, but can provide significant benefits for the heavy-heavy class as well. Real time combustion control with cylinder pressure sensing is now possible as sensors are available commercially at reasonable prices, and cylinder pressure sensing is already being used in some light duty diesels.

DDC has estimated a thermal efficiency gain of 1 to 2 percent with advanced controllers with a 37% NOx reduction as shown in Figure 3-7 above, indicating the potential for a FE gain of up to 5% with reduced emissions. It is possible that the NOx reduction could be traded for additional efficiency gains. Cylinder pressure sensors for light duty diesel engines have been commercialized at a cost of about $50 per cylinder. Even if heavy duty sensors were twice the price, the sensors and wiring should add about $700 to the cost (or $1100 to RPE) of an in-line 6 cylinder engine.

Gas exchange losses are also helped by the electrically assisted turbo and/or sequential turbo, but the other technologies to attain this goal include an **EGR pump** and variable valve actuation. The EGR pump is a positive contributor to fuel economy only at very high EGR flow rates that may be required to meet the NOx standards without the use of urea-SCR. As engines planning to use in-cylinder control technology appear to be moving to a sequential turbo, low and high pressure loop EGR system, the potential for the EGR pump appears small and no manufacturer has embraced this technology.

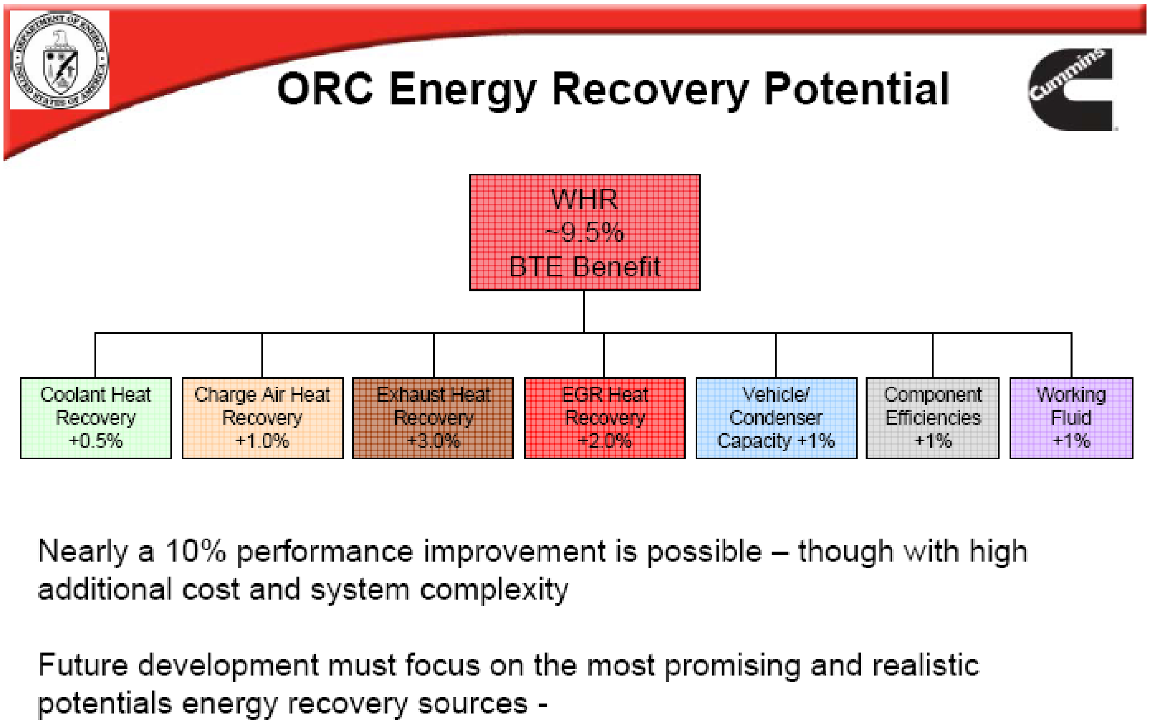
Variable Valve Timing (VVT) can be used to reduce gas exchange loss by increasing valve overlap to increase internal EGR but this would require a DOHC system, which is used in some but not all heavy-duty engines. In addition, it can be used to increase exhaust temperature if needed. Such a system could increase FE by 0.5% to 1.0%, but performance data on prototype systems have not been released publicly. The timing could be changed using hydraulic cam phasers similar to those that have been employed in light duty SI engines. Variable valve actuation is expensive for HHDT engines and has a payback of about 3 to 4 years, with a cost of about $800.

3.4 WASTE HEAT RECOVERY

Waste heat recovery is a major requirement for meeting the 50% thermal efficiency goal for the 2020+ time frame. As noted, mechanical turbo-compounding has been introduced by Daimler (DCC) in the new 2010 DD15L engine. Daimler claims a fuel economy benefit of about 3 percent for this feature, which is consistent with estimates of 2.5 to 3 percent in the literature, with a net RPE impact of $2500 to 3000. These new engines feature a high efficiency non-VGT turbo and a new low friction design, with urea-SCR after-treatment. DDC has claimed a fuel economy benefit of 5% for the urea-SCR/ new engine combination relative to the 2007 Series 60 engines that certified at 1.2 g/bhp-hr.

The electrically assisted turbo extracts power from the waste heat and many manufacturers have looked into this technology as an alternative to mechanical turbo-compounding. The case where the turbocharger is directly connected to the motor generator is conceptually attractive as the electric system can drive the turbo at low engine RPM to provide more boost and extract electric power at high RPM and load, while avoiding waste-gating. This system has been difficult to execute in the high temperature environment of the turbocharger, and simpler systems have been studied. John Deere has investigated a concept which is similar to the mechanical turbo-compound in its setup of a single turbocharger with an additional turbine operating independently to recover exhaust waste heat. In the electric turbo-compound case, the turbine drives a generator, rather than being coupled to the engine output shaft. This permits very flexible operation of the turbine and the recovered electrical power can be stored in a battery and used as required. However, costs are high (estimated at around $9000) as the system requires a generator, power storage and a motor to convert the power back to shaft work. Deere has demonstrated a fuel economy potential of 7 to 10 percent at full power over a broad speed range, but efficiency over a driving cycle is estimated at 5 to 6 percent, which also accounts for power storage and re-conversion losses. The electric turbo-compound is potentially more attractive as part of a hybrid system described in the following sub-section of this report.

The highest potential for waste heat recovery is through the Organic Rankine Cycle which uses a Rankine bottoming cycle to recover waste heat lost in the exhaust, EGR and water coolers. Cummins has identified a potential of almost 10 percent benefit, but the most potential is in the Exhaust and EGR heat recovery. A simpler system focused on



these sources could yield a 6 to 7 percent benefit according to Cummins and could potentially be lower cost than a electric turbo-compound system, implying a cost of about \$6000 to 7000 . However, such a system is unlikely to be commercially available until about 2020.

3.5 FRICTION LOSS

Friction losses can be reduced through redesign of moving components and through the use of low friction coatings. Figure 3-8 shows the contribution to friction of the different components. The effect of friction reduction on diesel engines is estimated at about 0.4 percent per 10 percent reduction in friction for a highly turbocharged engine on the highway cycle, but can be as large as 0.8% per 10 percent on a medium duty engine running at an average load of 35 to 40 percent of peak torque, excluding idle.

As can be seen from the figure, the basic piston skirt, rings, rod bearings and crankshaft account for about 50% of total friction loss (the figure also shows gas pumping loss across the valves, and in the turbo and intake manifold, which is not included in this estimate).   Friction reduction is an evolutionary process involving coatings, component redesign and the use of new materials in contact surfaces. Manufacturers agree that friction reduction of 5 to 10 percent will occur in the near term and 15 to 20 percent is possible by 2025. In addition, the downsizing and increased BMEP of engines reduces friction as a percent of engine output, so that the total decrease in friction as a percent of engine output can be in the 25 to 30 percent range by 2025. This value is somewhat lower than the Cummins estimate of 33 percent friction reduction required to meet the DOE 55 percent efficiency goal. We have used this estimate to derive the net efficiency improvement.

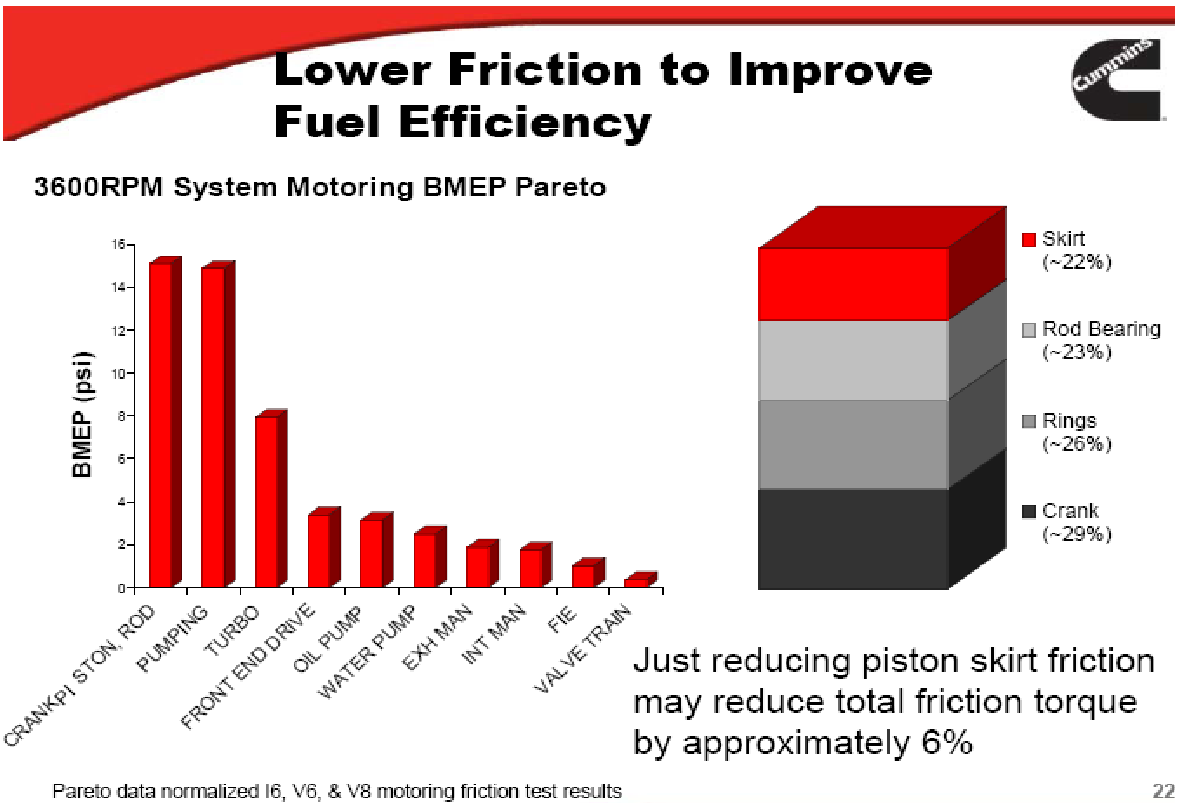


Figure 3-8: Friction Loss Allocation to Components in Engine

The use of friction reducing cylinder and piston coatings is expected to be very cost effective with a cost of about $250 and a payback of about 0.5 year. Friction reduction in the front end drives, crank journal bearings, and engine accessories are only somewhat less cost effective with a cost of about $500 at a payback of about 1 year.

3.6 ACCESSORY POWER LOSS REDUCTION

Accessory drive power for power steering, the cooling fan, water pump, oil pump and the HVAC unit can be supplied electrically, but the power requirements can be very large to meet peak demand as opposed to average power demand. Figure 3-5 shows estimates from IVECO (an Italian truck manufacturer) on the peak and average power demand of various accessory drives for a heavy truck. In total, there is a 9:1 ratio between peak and average demand but the high peak demand makes it difficult to electrically power all accessories. Typically, the cooling fan can be powered by a clutch drive to eliminate the largest peak power demand but even the remaining accessories cannot be easily electrified unless substantially more electrical power is available on-board, implying the need for hybridization.

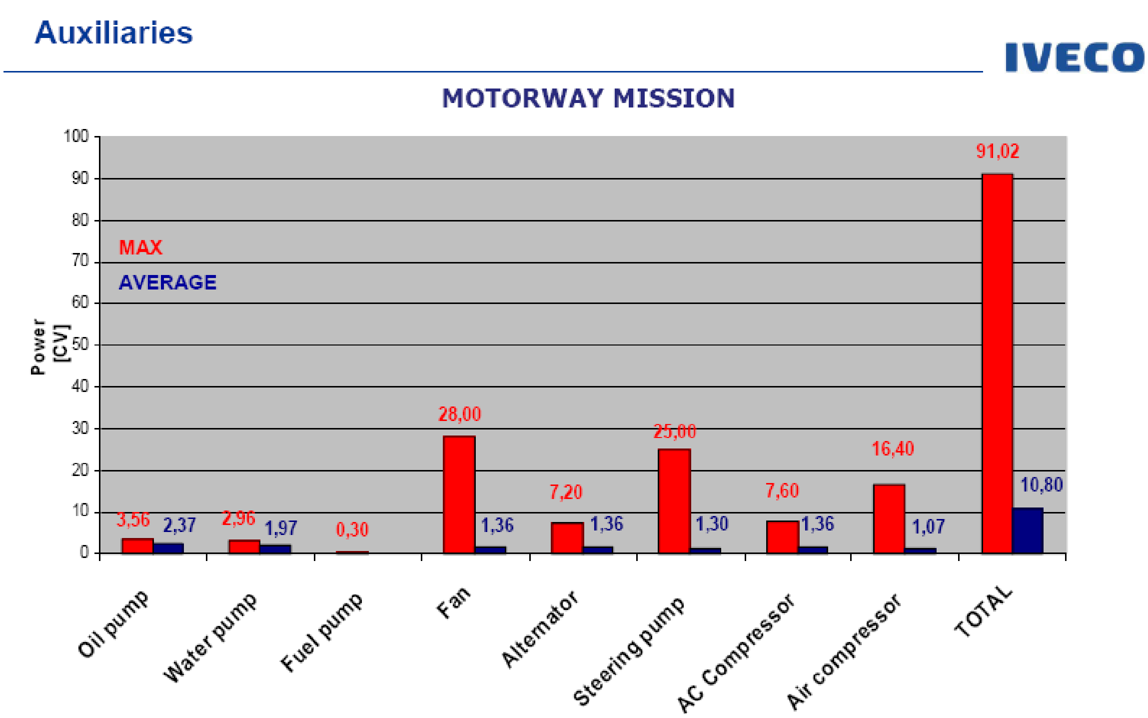


Figure 3-5: Peak and Average Power Demand for Accessory Drives in a HHDT

The 10.8 HP average demand indicated is approximately consistent with the estimate by Cummins of 6 percent of energy for accessories on the line haul cycle that requires 173 HP average power. In terms of average demand, the oil and water pump are the two highest and have a modest peak to average ratio of power so that electrification is not very expensive since the drive motor size is limited. Fuel savings from electrification is not due to electric drive (since the electricity is derived from the engine driving the alternator) but from reduced use as electric drive permits tailoring to demand. From this perspective, the water pump, power steering pump, air conditioner compressor and air compressor offer savings since they need not be running or be running at reduced speed much of the time. The oil pump electrification may not provide significant fuel economy benefit but may allow lubrication improvements to allow some friction reduction and is also a candidate for electrification.

3.7 TRANSMISSION IMPROVEMENTS

The oil pump and water pump can be electrified with some strengthening of current vehicle electrical systems and battery capacity, but the other accessories will need significant amounts of power to meet peak demand, and cannot be easily included unless it is part of hybrid system where there is ample electric power on board. Estimates form manufacturers suggest that the oil and water pump may provide 0.6 to 1.0 percent benefit at a cost of about $1000, while electrification of all candidates could provide 2 to 2.5 percent benefit in fuel economy at a cost of about $2500 for line haul trucks. In medium duty trucks the same accessories could provide about twice the gain from electrification since accessory loads are a much larger part of total fuel use. In addition, vocational use MDT have power take off driven external accessories like a mobile crane or a refuse crusher, where there are significant prospects for fuel use reduction that are very application specific.

As noted, most heavy-heavy duty trucks use the 10 speed manual transmission and most do not feature direct drive in top gear. In Europe, there has been a significant shift to 12 speed transmissions with many featuring the “I-shift” AMT design. Experts at ZF indicated that the 12 speed transmission with direct drive in top gear offers a 1 to 1.5 percent in fuel economy over the standard 10 speed overdrive transmission, as shown in Figure 3-6.

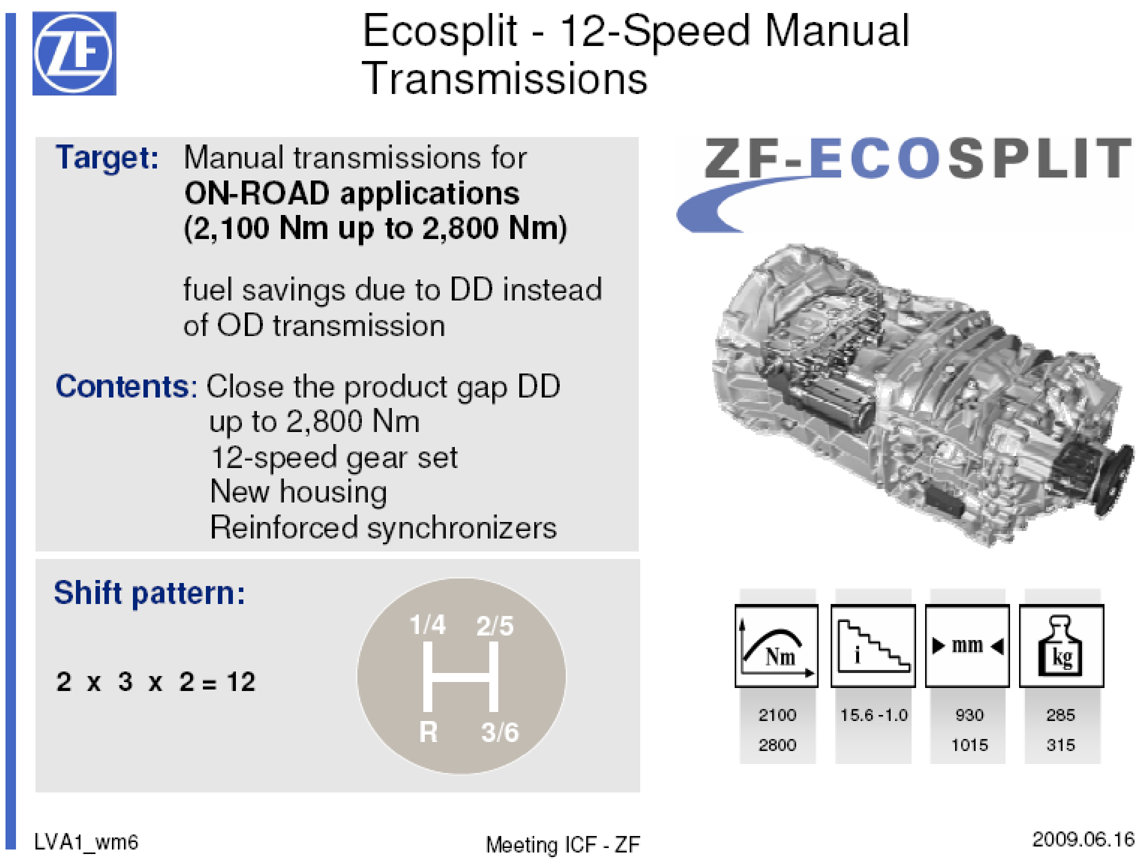


Figure 3-6: ZF Transmission Details

"I-shift" is a brand name given by Volvo for its 12 speed automated manual transmission (AMT), and this type of AMT has also been introduced by ZF in Europe (the shift pattern for these transmissions is in the form of an I as shown in Figure 3-6). These second generation AMT models introduced in 2008/9 are substantially superior to the first generation models introduced around 2000, and this has been made possible by closer integration of transmission and engine controls. For example, the current AMT models automatically disengage the clutch on downhill sections of rolling hills, and provide faster and smoother shifts than is possible from a conventional manual due to the control integration. AMT manufacturers concede that the best drivers can equal the performance of an AMT but state that on average, fleets see a gain of 3 to 4 percent in fuel economy. Even larger gains are observed with poor drivers, and the lack of experienced drivers could be a major market force for the AMT. The new AMT models also claim to offer improved clutch and brake wear, so that fuel savings are only a part of the total savings realized. In Europe, ZF estimates that the payback period for these transmissions is under

3 years. Given the lower fuel price in the US, payback will be longer. Currently, an AMT for a Class 8 tractor is a $9,000 to 10,000 option relative to a manual transmission, and even at a 4% fuel economy gain on average, payback on fuel savings at $3 per gallon is around 4 years, and could be close to 3 years if clutch and break wear benefits are considered. Manufacturers report that AMT penetration has increased in 2008/9 to about 15 percent of sales when fuel prices increased sharply.

As noted in Section 2, about three quarters of all medium duty trucks use automatic transmissions and the use of an AMT can provide fuel savings in the 7 to 9 percent range by eliminating the torque converter loss and by the use of more efficient gear sets. However, the shift quality of the AMT is not as good as that of an automatic, while the torque at launch is also lower since there is no torque multiplication in the torque converter. Hence, acceleration will be inferior to that of an automatic and some believe that the AMT reduces truck productivity in typical urban driving cycles. Newer generations of the six speed AMT for medium duty trucks have addressed some of these problems and will likely be more competitive in the future. In addition, the AMT may require more maintenance relative to a conventional automatic transmission, so that fuel savings alone may not provide a correct indication of payback. However, the AMT is cost competitive with an automatic transmission in terms of first cost and the value of fuel savings is on the order of $800 to $1000 per year. Hence, even with a large negative hedonic valuation of $2000 to $3000 for drivability and maintenance effects, payback on the order of 3 years is possible.

3.8 HYBRID DRIVETRAINS

Hybridization of the truck drivetrain is in principle, similar to the hybridization of passenger cars and many of the same design types under consideration: series, parallel and two-mode. One interesting addition to the available hybridization technologies is the hydraulic hybrid, which stores power in the form of a compressed fluid rather than in a battery. However, the series hybrid appears too expensive and heavy for most truck applications (it may be suitable for buses). The two-mode hybrid may also be too complex and expensive for most truck applications and the manufacturers appear to be considering only the parallel hybrid for most applications and the hydraulic hybrid for selected applications.

The most popular parallel hybrid configuration is similar in both the EU and the US is the use of a electric motor sandwiched between the engine and transmission. Either a single clutch (between motor and transmission) or two clutches (also between engine and transmission) is employed, with the single clutch system being more dominant, since motor sizes do not permit pure electric drive at present. Physically, this system closely resembles the Honda integrated motor assist (IMA) system used in passenger cars, although the motor size and battery are three to four times larger for truck application. Typically motor sizes are in the 50 + 10 kW (peak) range, and the vast majority of systems have been used on medium duty Class 6 and 7 vehicles operating on city duty cycles ranging in speed from 4 to 20 mph. The Eaton system used by Kenworth and Navistar on their vehicles has a motor rated at 44 kW peak and a battery with energy storage capacity of 1.8 kWh, as an example The system is mated to a six speed AMT. ZF in Europe has very similar design with the motor rated at 60 kW. Current system strategy is to provide launch and acceleration assist to the engine and recover braking energy, but many systems do not provide idle stop, and do not downsize the engine to preserve full load continuous operating performance.

A comprehensive analysis of hybrid potential for trucks is outside the scope of this study and only some general parameters relating to hybrid benefits are examined. Most of the available data for trucks (as opposed to buses) from on road testing in the US is on the Eaton system and the following results have been reported:

- Hybrid class 4 vans operating in city pickup and delivery service (for UPS) showed an average fuel economy improvement of 29% for a cycle speed of about 20 mph
- Hybrid class 6 trucks tested by Navistar on the dynamometer over the city cycle showed a benefit of 24% in fuel economy, and about 20% on road cycles in California with speeds in the 20 to 30 mph range
- Hybrid class 6 trucks tested in New York over duty cycles with an average speed of about 5 mph showed a fuel economy benefit of 40%

In general, hybrid benefits increase with decreasing speeds and increasing number of stop-and –go operations. It should be noted that the UPS van comparison was an AMT hybrid compared to a diesel van with an automatic transmission tested by Navistar, so that the hybridization benefit was in the low 20% range consistent with Navistar data from California.

Although there have not been any detailed testing of class 8 hybrids in the US operating on long haul routes, Volvo testing in Europe has shown that typical long haul operation (potentially similar to the long haul cycle discussed in section 2) has enough acceleration and braking events to provide a 3 to 4 percent improvement in this application with a 25 kW motor. Simulations by the Southwest Research Institute (SwRI) with a 55 kW motor showed a hybrid benefit of 5.7% in fuel economy, although the cycle specifics were not provided. Volvo also claimed that hybridization made accessory electrification easier, so that they were able to attain 5 to 6 percent fuel economy benefit in European testing even with the smaller motor size.

Current hybrid systems with a 50 kW motor and about 2 kWh of energy storage add about $40 to $50 thousand to the price but this is at very low annual sales volumes, probably less than 1000 units per year. Manufacturers are contemplating using essentially the same system across a wide range of truck weights and applications, with different benefits. Near term (2014-2015) target prices assuming volumes of about 10 to 20 thousand per year are in the $20,000 range, and it appears possible that an additional 25 to 35 percent reduction in costs could occur from 2015 levels by 2025 if expected battery and motor price reductions occur from both scale and technology. Plug-in hybrids are also being contemplated although a 40 mile range would require a battery of 50 kWh or more for a medium duty class 6 truck with attendant very high costs.

Hydraulic hybrids have the capability of absorbing high power spikes due to the mechanical nature of energy storage, but total energy storage capacity is very limited. In addition, the system is quite bulky and space and weight requirements for the hydraulic tanks limit its applicability. Truck manufacturers believed that hydraulic hybrids are well suited for some applications with extreme stop and go cycles like garbage trucks. At the same time, they did not believe that these market niches could support adequate sales volume to attain scale and scope economies, unlike an electrical hybrid powertrain, suggesting that markets for such hybrids would not develop to commercial scale.

3.9 SUMMARY

Engine benefits are summarized in Table 4 below for two of the three cycles defined in section 2: the long haul cycle (highway), and the city/highway cycle (regional). The low speed cycle is not well characterized for engine improvements as the effects of engine technology on idle consumption have not been reported, and idle and very low speed use are major components of the cycle. However, the benefits at low speed should be comparable to but slightly lower than the benefits on the regional cycle as some improvements like friction reduction and accessory improvements will have larger benefits while others such as urea-SCR and turbo-compounding have lower benefits.

Table 4: Engine and transmission related fuel consumption reduction (%)

Relative to MY 2008 engine/ 10-speed manual at constant 2010 emission standards for Class 8B truck

Technology		**2009 -2017**		**2009 – 2025**	
		Highway	Regional	Highway	Regional
Urea SCR		3.0*	2.0*	5.0	4.0
Closed loop combustion control		1.5	1.0	3.0	2.0
2500/3000 bar fuel injection		0*	0*	1.0	1.0
Sequential turbo/ down-sizing		0*	0*	0.5	0.8
Cooled EGR		1.0	1.0	1.5	1.5
Variable valve actuation		-		1.0	1.0
Mechanical turbo-compound		2.5	1.3	3.0	1.5
Electric turbo-compound		5.0	2.5	6.5	3.3
Organic Rankine cycle		-		6.5	3.3
Friction reduction		1.0	1.5	1.5	2.2
Improved accessories		0.5	0.8	0.7	1.0
Electric accessory drive (oil/water/steering/air compressor)		2.0	3.0	2.0	3.0
Maximum Engine total		**13 to 15**	**12 to 14**	**23 to 27**	**21 to 23**
Hybrid (50 ± 10 kw motor)		3 to 4	6 to 7	4 to 5	8 to 9
Transmission 12 speed with DD		1.5	1.0	1.5	1.0
AMT compared to average driver		3	5	3	5
Engine and Transmission Lubricants		1.0	1.5	1.5	2.2

Note: Technology benefits are not additive, and some technologies cannot be used together with others on the list
 * Technology required for 2010 standard

4 AERODYNAMIC DRAG, ROLLING RESISTANCE AND WEIGHT REDUCTION

4.1 AERODYNAMIC DRAG REDUCTION TECHNOLOGIES

In basic terms, an aerodynamic drag force can be expressed as:

$$F_D = C_d * \rho * A * V^2/2,$$

where:

- F_D is the drag force,
- C_d – drag coefficient,
- ρ – air density,
- A – vehicle cross-sectional reference area, and
- V – effective speed (compounded from vehicle speed and a wind directional speed component).

While a truck cross-sectional effective area is dictated by its size requirements, the drag coefficient and vehicle effective speed are the two most significant components in determining the force required to overcome air resistance.

Since the drag force varies as the square of wind speed, its contribution to fuel consumption is significantly higher at highway speeds. Peterbilt has shown that (assuming steady state driving in undisturbed air) the aerodynamic drag component becomes the largest demand for power at speeds above about 50mpg, overtaking

Figure 4-1: Steady-state Tractor/trailer Aerodynamic Drag vs. Speed, Compared to Rolling Resistance. Source: Peterbilt.

rolling resistance as the leading component for fuel consumption. The power requirement becomes especially large at highway speeds. For example, as indicated in Figure 4-1, when speed changes from 60mph to 70mph, the power requirement to overcome drag increases by 50%, assuming a fully loaded truck.

For a fully loaded Class 8B tractor/trailer system (80,000 pounds GVW), the energy distribution diagram, as provided in the US DOE's 21st Century Truck Program publications, lists the base energy consumption (assuming steady cruising at 65mph on level road) as 255.5 kilowatt-hours (kWh). Also, as a reference, the target energy level, according to DOE goals, is listed for the truck as 161 kWh. Assuming the energy use target for aerodynamic drag of 68 kWh is achievable, the reduction corresponds to 20% figure from the base drag energy consumption of 85 kWh. Since the base aerodynamic drag consumes 52.8% of an engine output of 161 kWh (85/161), 20% drag energy reduction would result in about 10.6% energy and fuel consumption reduction (0.528*0.2). This figure should be discounted for real world conditions such as rolling hills or traffic, even under the assumption of highway-type driving. Therefore, if aero drag is 38% of fuel use in the line haul cycle as specified by Cummins, the expected fuel savings from 20% reduction in aerodynamic drag is only about 7.6%.

It should be noted that, while air pressure on frontal truck surfaces is a large contributor to aerodynamic drag, studies have shown that for a typical tractor/trailer system, very large drag occurs in low pressure zones created in the gap behind the tractor, under the vehicle and behind the trailer. Figure 4-2 provides a pictorial illustration of how these turbulent low pressure zones are created. In general, aerodynamic treatments of these large problem areas are designed to minimize pressure differentials by either preventing high speed air circulation and/or providing a surface to which the separated air flows can be redirected and "reattach" with minimal turbulence.

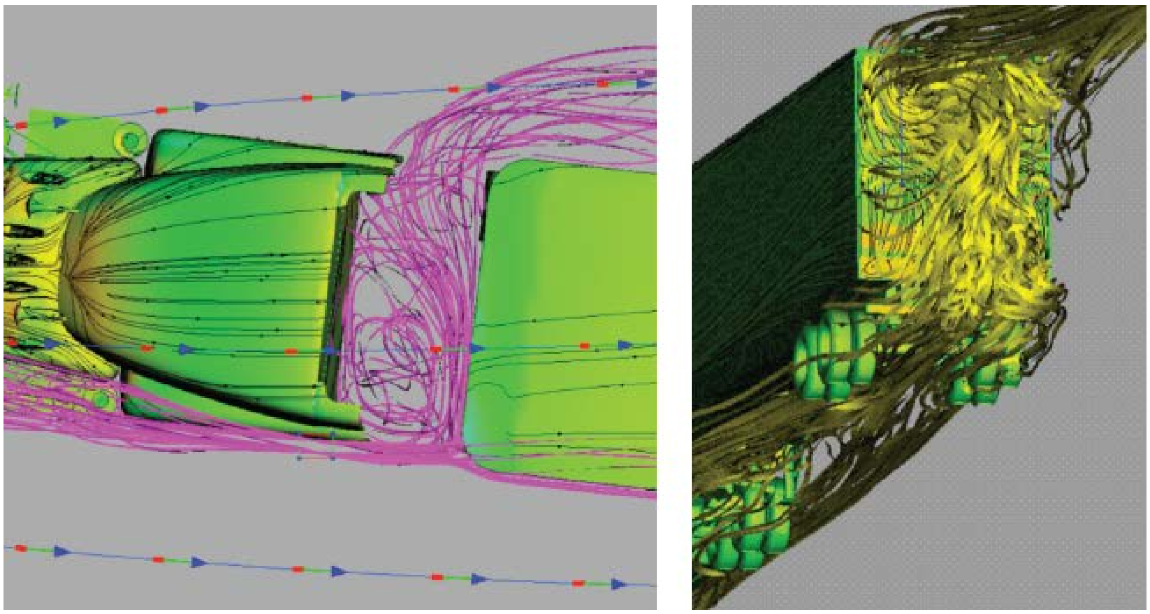


Figure 4-2: Simulation analysis of air flow around the tractor/trailer system.

Turbulent areas represent low pressure zones, large contributors to overall aerodynamic drag. Source: Peterbilt.

The rest of this section focuses on a literature review of aerodynamic drag reduction technologies and our interpretation of published fuel consumption reduction results. For the purposes of this discussion, all estimates for fuel consumption improvement assume the line haul cycle, unless otherwise noted.

4.1.1 Tractor Aerodynamic Improvement Technologies

Truck OEMs have claimed significant progress over past two decades in reducing drag coefficient of a typical Class 8 tractor with a smooth-sided 53-foot trailer from about 0.8 to 0.6 to 0.65, an improvement of 19 to 25%.[22] This level of drag reduction was achieved

[22] Rose McCallen, et. al., Aerodynamic Drag of Heavy Vehicles (Class 7-8): Simulation and Benchmarking", SAE Technical Paper 2000-01-2209

by aerodynamic refinements such as roof fairings, cab/trailer gap devices, side fairings and a tractor front body streamlining. US EPA's SmartWay^{SM} guidance[23], states that this level of tractor aerodynamic drag reduction improves fuel consumption 13 to 17 percent as compared to "classic" style trucks with no drag optimization steps taken. These figures are supported by manufacturers such as Kenworth, which claims that their newest generation tractors T600 or T2000 can get up to 17% better fuel consumption compared to traditional "long nose" trucks with no aerodynamic devices[24]. However, this is almost double the effect computed from the line haul cycle approach discussed in section 2.

Figure 4-3 provides a comparison of technologies available on most tractors today with aerodynamic improvements that include sloped hood, air dam, covered intake, side fairings and an aerodynamic roof fairing. Many of these devices can be obtained from aftermarket manufacturers as bolt-on additions so the cost of these basic technologies is widely quoted and range from zero dollars (aerodynamic design incorporated into truck bodies during regular product redesign cycle) to thousands of dollars for devices such as glass fiber side skirts or roof fairings sold in relatively low volume.

Figure 4-3. Aerodynamically Refined Tractor Geometry vs. Non-Optimized Tractor.

[23] The US EPA, "A Glance at Clean Freight Strategies, Improved Aerodynamics", the SmartWay^{SM} Facts Sheet, February 2004
[24] Kenworth Truck Company, "Push Less Air, Pull More Profit", a Guide to Increasing Fuel Economy, 2008

Most aerodynamics studies in the US focus on typical "front-engine" truck bodies. However, similar aerodynamic solutions are also applicable to "cab over engine" bodies as illustrated by Figure 4-4, which shows an innovative inflatable gap seal pioneered by IVECO in Europe.

Table 4-1 provides a compiled list of currently available aerodynamic drag reduction technologies most often quoted in the literature. Fuel consumption improvement ranges, as well as the baseline technology identification are also provided together with some of the main roadblocks for market implementation, as commonly identified by truck

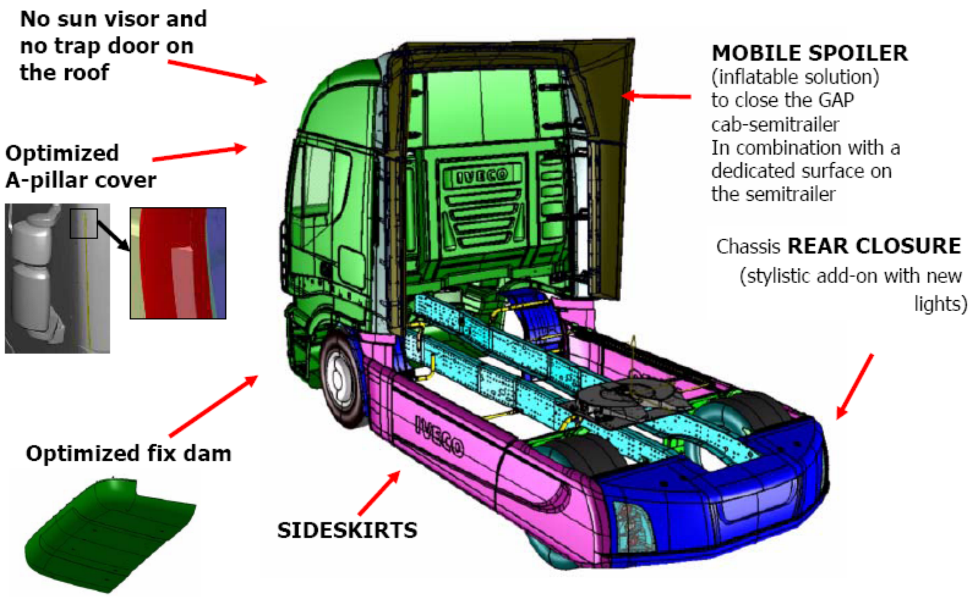


Figure 4-4: Cab-Over-Engine Aerodynamic Improvement Technologies.
Source: Iveco.

Operators. The roof fairing designed to shield an upper face of a trailer is claimed to be the most significant fuel efficiency technology available for tractors with no major implementation issues beyond add on costs.

We believe that historical 25% reduction in aerodynamic drag (from about 0.82 to 0.62) with the streamlined tractors and gap treatment is a defensible estimate. The best in class solutions in 2009 claim a drag co-efficient of 0.55 to 0.57, and anecdotal information from manufacturers suggests that about 35 to 40 percent of Class 8 tractors sold in 2009 are at or close to that level (many do not include the tractor side skirts and aerodynamic mirrors and may be at a 0.58/0.59 drag coefficient). Another 35 to 40 percent of the market do not purchase the “full’ aero package but have only the full roof fairing (possibly those used in regional haul) and may be at drag coefficients of 0.62 to 0.65, while 15 to 20 percent opt for the “classic” look at a drag coefficient of 0.71 to 0.75 with a roof deflector . This distribution yields an average drag coefficient of 0.62 for the 2009 fleet of tractors used to haul van trailers. However, the estimates of up to 17% fuel consumption improvement from the 25% level of drag reduction is highly optimistic and potentially reflects idealized driving scenarios. The line haul cycle based computation would yield a 9.5% fuel economy benefit in real-world operation.

Table 4-1: Tractor Aerodynamic Improvements and Fuel Consumption Estimates.

Technology	**Fuel Consumption Improvement [%]**	**Compared to base configuration…**	**Implementation Issues**
Trailer Gap 38 inches	1.2 ± 0.3	Gap 46 inches	Turn radius reduction
Trailer Gap 25 inches	0.7 ± 0.2 1.6 ± 0.3 3.0 ± 1.0	Gap 35 inches Gap 46 inches Gap 65 inches	Turn radius reduction
Cab Roof Deflector	4.0 ± 1.0	No deflector	
Full Roof Fairing	6.0 ± 2.0	No deflector or fairing	
Full Roof Fairing (with roof cap and rubber trim)	7.0 ± 2.0	Raised roof sleeper	
Cab Gap Extender (with rubber trim)	2.0 ± 0.5	No gap treatment	Turn radius reduction, compatibility with trailer
Improved Air Dam Front Bumper	1.5 ± 0.3	Standard bumper	
Tractor Side Skirts	2.0 ± 1.0	Exposed fuel tanks	Brake cooling, snow/ice buildup, ground clearance
Remove Bug Deflector	1.0 ± 0.5	Bug deflector	Bug accumulation
Radiator Shutters	0.5 to 2 1 to 3	No shutters – summer No shutters – winter	Engine Cooling Issues
Under-hood air cleaners	1.5 ± 0.5	Cowl mounted air cleaner	Packaging issues
Aerodynamic mirrors	1.2 ± 0.3	Regular mirrors	Visibility

Estimates for steady-state level driving at 65mph

Furthermore, the literature tends to report combined fuel consumption improvement figures of discrete aerodynamic devices as additive. For example, adding together all possible devices that can be combined on a single truck from Table 4-1 yields a fuel economy improvement of about 17%, but the non-additive nature of benefits yields an actual combined benefit of around 10 to 12 percent at a continuous 65 mph and only 7 to 9 percent on the line haul cycle. Fuel consumption benefits of discrete technologies cannot be added together, since any single aerodynamic device will alter overall system air flow and, therefore, benefits from other "downstream" devices will be different. Using the line haul cycle effect as described above, the defensible figure associated with 25% drag reduction should be about 8%, as the nominal historical fuel consumption improvement estimate over 25 years compared to a base tractor/trailer with no aerodynamic enhancements. This value implies an annual fuel economy improvement from aerodynamics alone at 0.38%, which is still well above the fuel economy survey data based estimate of 0.2% to 0.25% per year for the combined effect of aerodynamic and rolling resistance improvements. This implies that as aerodynamics becomes a smaller part of engine load, the net benefits decrease from about 4% per 10 percent drag reduction to 3.5% or less.

Future tractor aerodynamic improvements will require more comprehensive streamlining of the truck exterior; these technologies are already being demonstrated by manufacturers. Peterbilt has performed wind tunnel testing and determined that even with today's aerodynamically refined tractor geometries, opportunities exist in drag "hot spots" such as tractor/trailer gap, windshield, and radiator grille/bumper system (see Figure 4-5)[25]. Freightliner's Innovation Truck program is another example that has shown a similar approach. The Freightliner designs build upon their Cascadia model 2007-level technology package and include rear wheel fairings, underbody panels and front bumper air splitter to smooth air flow in the corresponding areas. Also the program has demonstrated side view cameras in place of traditional mirrors.[26]

The total feasible drag reduction from current levels obviously depends on the base vehicle geometry. For example, lighter "straight" trucks (i.e., unarticulated single units, with truck and cargo container build on the same chassis, mostly falling into Classes 6

[25] Peterbilt, "Truck Aerodynamics and Fuel Efficiency", White Paper, 2008
[26] Daimler Press Release, "Daimler Trucks North America Previews Latest Technologies on New Innovation Truck at Mid-American Trucking Show", March 19, 2009.

and 7) will not have a gap between the truck body and container so the overall drag improvement potential will be smaller. Once again, the major applicability issue is how the trucks are used, i.e., primarily in city or suburban driving, or primarily interstate-type high speed driving patterns. All trucks have the potential to adopt technologies such as aerodynamic mirrors, bumpers and fuel tank fairings.

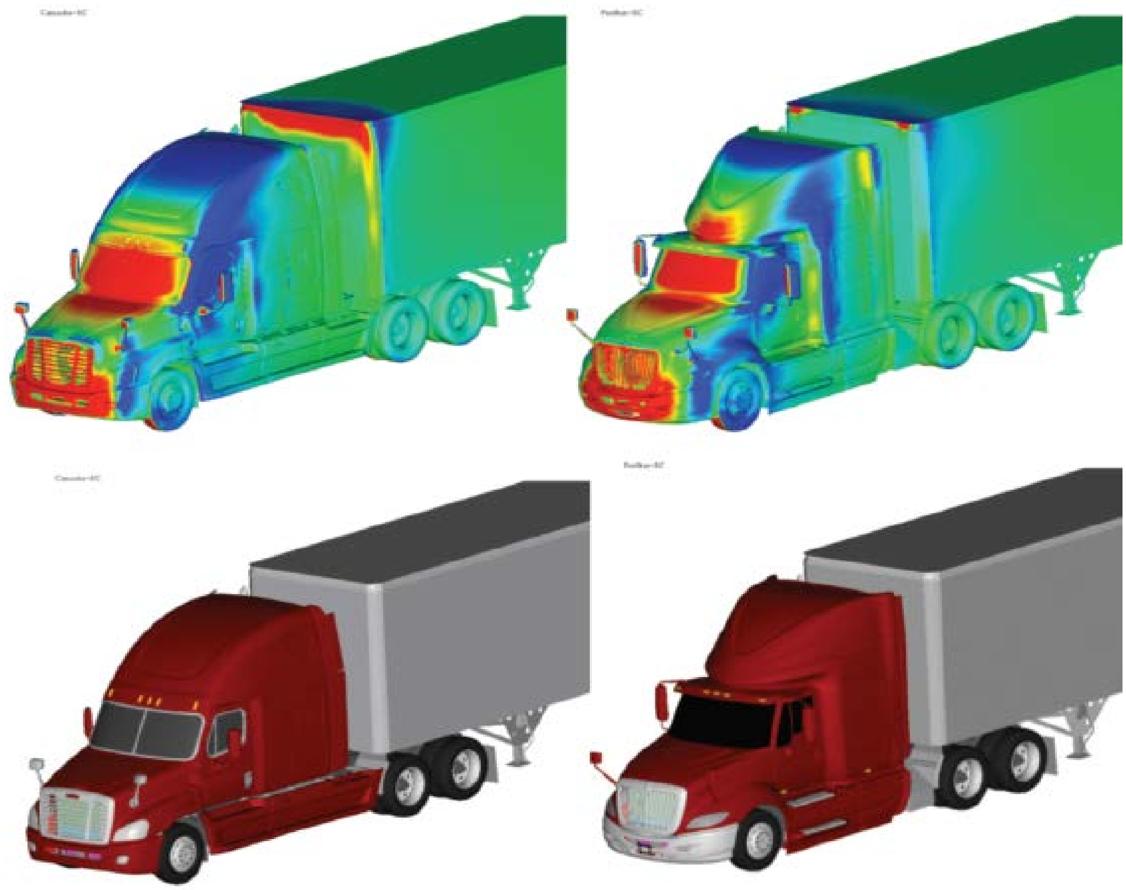


Figure 4-5. Peterbilt truck drag hotspots and resulting aerodynamic design improvements. In general, aerodynamic drag reduction technologies are applicable to any truck class but

4.1.2 Trailer Aerodynamic Improvements

The basic rectangular shape of a van trailer offers significant opportunities for improving the aerodynamics and fuel efficiency of the tractor-trailer system. Existing trailer technologies are primarily designed to reduce turbulent air flow in the front (in the tractor-trailer gap), the underside (between the rear tractor tires and the rear trailer tires), and the rear (behind the rear doors). Solus-Solutions has shown that these areas contribute about 75% of the total drag created by the trailer, which can be further divided as 30, 35 and 35 percent for each of these locations, respectively. Figure 4-6 provides examples of practical solutions for these problem areas. Trucks with other trailer types such as flat beds, auto carriers, or stake beds, therefore, can have only relatively small improvement to aerodynamics from items such as side skirts or diffusers.

Figure 4-6: Trailer Aerodynamic Devices

Photos above, from left to right, Side Skirts, Front Fairing, Tail Fairing. Sources: Layton Composites, Nose Cone Manufacturing, ATDynamics and Iveco.

Solus-Solutions claims that addressing the three trailer problem areas, a combined 10% fuel consumption improvement can be achieved at highway speeds[27]. Other literature sources we have examined provide further indication concerning claimed fuel consumption improvement that the discrete trailer devices can achieve and Table 4-2 provides a list of these estimates as well as the implementation issues as reported by truck operators.

[27] R.M. Wood, Solus-Solutions and Technologies, “Operationally-Practical and Aerodynamically-Robust Heavy Truck Trailer Drag Reduction Technology”, SAE Technical Paper 2008-01-2603

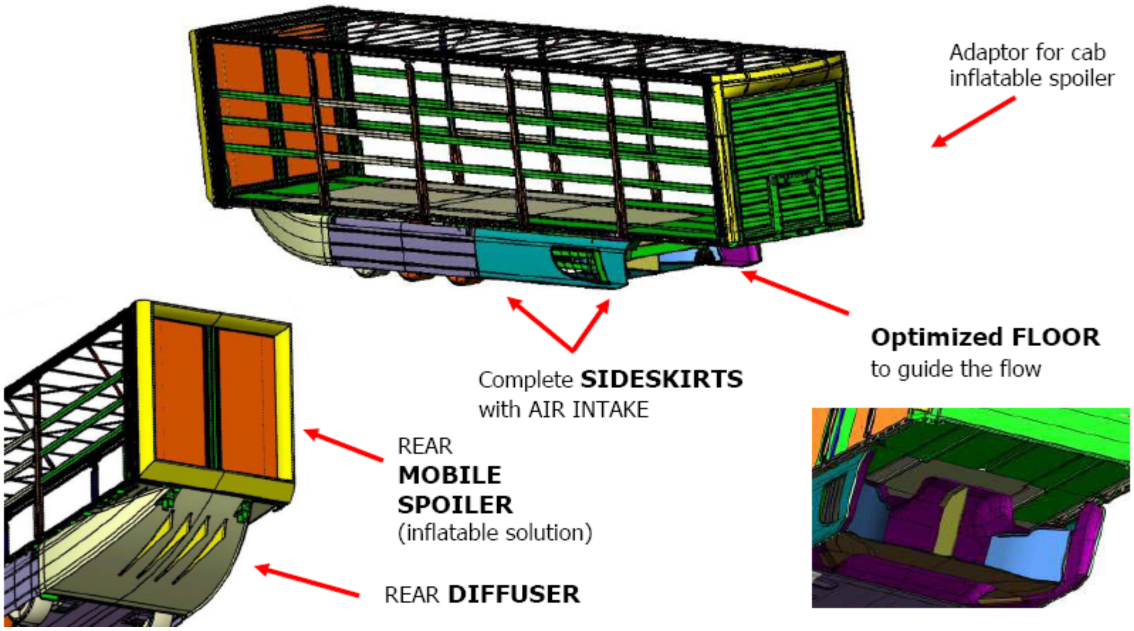


Figure 4 -7. Trailer Aerodynamic Drag Reduction Technologies.

This data appear to confirm that 10% fuel consumption improvement is possible at 65 mph with the smooth sides, trailer side skirts and boat tail. However, it is likely that some portion of this benefit can be attributed to the gap treatment technologies built onto tractor bodies and likely include the contribution from the tractor roof fairing.

Table 4-3 itemizes RPE ranges for the trailer aerodynamic devices as reported by various aftermarket manufacturers[28]. When these estimates are used to compute nominal cost effectiveness, it can be observed that the market values these devices in a range from \$228 to \$495 per each percent of claimed fuel efficiency gain. The average cost effectiveness for this data sample is \$360 per 1% improvement.

[28] CK Salter, Presentation Before NAS Committee, June 18-19, 2009

Table 4-2. Trailer Aerodynamic Drag Improvement Technologies and Claimed Fuel Consumption Improvements

Technology	**Fuel Consumption Improvement [%]**	**Compared to base configuration…**	**Implementation Issues**
Smooth trailer sides	2 to 4	Trailer with exterior posts, no side curtains	
Side skirts	Up to 7	No skirts	Ground clearance issues, snow/ice accumulation, brake cooling
Boat tail	3 to 5	Regular base	Trailer length restrictions, door accessibility, docking issues
Inflatable tail	Up to 3	Regular base	Trailer length restrictions, door accessibility, docking issues
Trailer base vortex generators	Up to 3	Regular base	Trailer length restrictions, door accessibility, docking issues
Trailer face fairings	1 to 3	Regular face	Turn radius reduction
Nose cone	Up to 4	Regular face	Turn radius reduction, compatibility with tractor

Estimates for steady-state level driving at 65mph(?)

Table 4-3. Trailer Aerodynamic Device Manufacturer Responses Concerning their Product Costs and Fuel Consumptions Benefits

Technology	**Claimed Fuel Consumption Reduction %**	**Incremental RPE [$]**	**Nominal Cost Effectiveness [$RPE/%FC]**
Trailer Skirts	6 7 7	1,900 1,599 2,400	317 228 343
Trailer face devices: Stabilized Nose Fairing Gap Fairing Nose cone	 1 2 2 4	 495 795 849 1,264	 495 398 425 316

4.1.3 Tractor/Trailer as a System

Since the fuel consumption benefits are difficult to segregate into trailer and tractor portions, especially because the gap treatment device benefits can overlap between the trailer and tractor technologies, we have focused on the tractor/trailer system analysis as more appropriate approach to determine overall benefit potential.

Rocky Mountain Institute (RMI) has published a report claiming that advanced truck streamlining efforts should yield C_d of 0.45 for a tractor/trailer system or even lower[29]. Their claims were substantiated by results from Canadian Prevost articulated bus (size comparable to a typical Class 8 tractor/trailer system) wind testing program which demonstrated C_d result of 0.384 (with full gap seal, low sides and flat streamlined front end). RMI does indicate that Cd of this level would be more difficult to achieve for a typical front engine/large radiator trucks with several horizontal geometry separations but they believe that C_d of 0.45 is achievable.

The U. S. National Academy of Sciences (NAS) is currently evaluating and compiling fuel efficiency improvement technology information and early results are available in public domain. The estimates include RPE figures compiled by TIAX and others although these estimates are still to be reconciled[30]. For class 8 truck aerodynamic devices, the NAS data includes estimated system level improvement in order to achieve various C_d targets. Table 4-4 summarizes these estimates as compared to a baseline 53-foot tractor-box trailer combination with total C_d of 0.63. The data illustrates that 0.45-level of C_d is achievable although it will require inclusion of advanced trailer enhancements.

When nominal cost effectiveness is calculated using data provide for the NAS committee, it can be observed that basic aerodynamic tractor devices, such as fairings and deflectors, and other aerodynamically redesigned components, such as mirrors, can be implemented in the market place at RPE per 1% improvement ranging from \$400 to \$500. More advanced next generation advancements, that includes "active" drag mitigation devices

[29] Rocky Mountain Institute, "Transformational Trucks: Determining the Energy Efficiency Limits of a Class-8 Tractor Trailer", July 2008.
[30] The National Academies, "Technologies Performance and Cost – Class 8 Truck and Trailer", Presentation by Committee Workgroup During April 7, 2009 Meeting.

(for example, inflatable gap reducers or retractable flaps), will require RPE per 1% improvement ranging from $500 to $900 or higher.

Table 4-4: NAS Estimates of Drag Reduction Technology

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Technology/Package	**Fuel Consumption Reduction [%]**	**Incremental Cost [$RPE]**	**Nominal Cost Effectiveness [$RPE/%FC]**
Cab top deflector, sloping hood, cab side flares	1.0 to 2.0	750	500
Aggressive aero cab: streamlined mirrors, cab side extenders, integrated sleeper cab roof fairings, aero bumper, full fuel tank fairings (**C_d ~0.55**)	3.0 to 3.6	0 to 2,750	417
Trailer streamlining: side skirts, aggressive trailer gap fairing (**C_d ~0.5**)	3.8 to 5.9	2400	494
Advanced trailer aero package: flow treatment devices and dynamic boat tail, side skirts and aggressive gap fairings (**C_d ~0.45**)	6 to 8.5	5,000	689
Pneumatic aero drag reduction devices	3.9 to 4.4	2,500 to 5,250	933

Baseline vehicle: 53-foot tractor-box trailer, 80,000pounds GVW, C_d=0.63

TIAX has shown that for lighter class 6 and 7 straight trucks the fuel consumption benefits of basic streamlining steps such as redesigned bumper or fuel tank wraps, would be similar, 1.0 to 2.0 % at an RPE of $750, which also translates to about $500 RPE per 1% improvement nominal cost effectiveness. More aggressive steps with additional technology, such as roof fairing and rear-mounted frame extensions for straight trucks, would achieve larger benefits, estimated at 5 to 8%, when compared to basic un-streamlined truck.

4.1.4 Aerodynamic Device Analysis and Summary

Significant aerodynamic refinements have been implemented by the heavy duty transport industry, but improvements were mostly integrated into tractor bodies, since no trailer owners were required to contribute. Most of the future potential for aerodynamic improvement is due to further refinement of the gap between tractor and trailer, underbodies, trailers, and to a much lesser extent improvements in tractor aerodynamics. Trailer improvements can be achieved at lower cost but are difficult to implement since trailers and tractors are often owned by different entities. The major institutional roadblock for trailer improvements is that their owners have no incentive to spend up-front capital with no direct benefit to them from fuel savings. Also aerodynamic trailer add-on technology was traditionally resisted by operators due such issues as cooling problems, ground clearance, durability and length limitations imposed on highway trucks. The use of devices such as inflatable adjustable gap seals, retractable skirts, or active devices should reduce incompatibility issues but will be more difficult to justify due to add-on costs and reliability concerns. The institutional trailer issues must be addressed before all of the benefits of the aerodynamic devices shown will be actually implemented widely in the market.

The potential for further aerodynamic drag reduction is highly dependent on base line truck configuration and duty cycle. Substantiating claims of fuel efficiency improvement by manufacturers, especially the aftermarket, is problematic, for two reasons. First, full scale independent wind-tunnel testing is costly and rarely available, and second, typical coast-down tests are hard to verify for marginal efficiency improvement technologies. Many researchers rely on truck scale model testing (typically 1:10 or 1:20 models) but OEMs such as Peterbilt believe that the scaled-down testing cannot be accurately translated into real-world performance, due to on-road variables such as wake interaction or the effect of rotating tires.

The EPA/DOT rulemaking has very similar data and has identified aerodynamic "packages" that combine discrete technologies. Its Bin 1 is the baseline with a C_d of 0.79, consistent with our data for the "classic" tractor-trailer. It has defined Bin 2, 3 and 4 packages with values of 0.72, 0.63, and 0.56 for C_d . The technologies are generally defined but not specific as manufacturers have to evaluate the actual aerodynamic performance to compute the C_d, which must fall within predefined values. EPA has also defined a Bin 5 with a C_d value of 0.51 for unspecified future improvements.

The literature we have examined indicates that the best tractor and regular trailer class 8 systems today (with aggressive gap treatment) achieve a total C_d of 0.56, which can be estimated to result in about 11% fuel consumption improvement on the highway route cycle when compared to old-style tractor/trailer with no aerodynamic streamlining at a C_d level of 0.79. Our estimates for the marginal (additive) benefits of technology, starting from a classic high roof tractor trailer with a drag coefficient of 0.79 is as follows:

Technology	EPA Bin	Drag Co-efficient.	% Drag Reduction*	%FC Reduction*	Cumulative FC %
Classic Cab & Trailer	1	0.790	Base	Base	100
Aero Cab I	2	0.742	6	2.3	97.7
Full Roof Fairing		0.668	10	3.8	94.0
Aero Cab II	3	0.628	6	2.3	91.8
Cab Gap Extender		0.609	3	1.1	90.8
Tractor Fairing/ Skirts		0.585	4	1.5	89.4
Aero Cab III	4	0.561	4	1.5	88.1
Additional gap/ mirror treatment		0.544	3	1.1	87.1
Trailer Side skirts	5?	0.501	8	3.0	84.5
Trailer Smooth underbody		0.481	4	1.5	83.3
Trailer Boat tail		0.457	5	1.85	81.7

* from previous step

Our analysis does suggest that, assuming the institutional tractor/trailer issues are addressed and there is adequate lead time, the advanced aerodynamic streamlining efforts should result in an additional 18.3 % reduction in drag coefficient (0.56 to 0.46) for new

Class 8B tractor-trailers with aggressive trailer enhancements. This level of C_d reduction would provide up to 6.4% additional fuel consumption improvement relative to the base classic tractor trailer. The FC consumption reductions are for the long haul cycle, and will be much smaller for the regional cycle due to its lower speed. The two levels identified in yellow high lights correspond to the average and best levels in 2008/9. Note that the fuel consumption reduction from the best level available today is 7.3 % (1-81.7/88.1) and is 11% relative to the average. EPA however, assumes that 10% of sleeper cabs are in Bin 1 and 70% in Bin 2, with the remainder in Bin 3 so that their baseline is higher, permitting a larger reduction in drag coefficient.

For low and mid-roof tractors, the frontal area is lower by 25% to 30% for the tractor which leads to much lower drag at the same drag coefficient. If the base classic tractor has a similar drag coefficient, the aero drag related fraction of fuel consumption would be reduced to 26% for a low roof tractor and 28.5% for mid-roof tractor. The tractor aerodynamic drag co-efficient reductions would be similar but the full roof fairing would not apply. Hence for the long haul cycle, the estimates of aero drag benefits for a low roof and mid-roof tractor without a van trailer would be as follows:

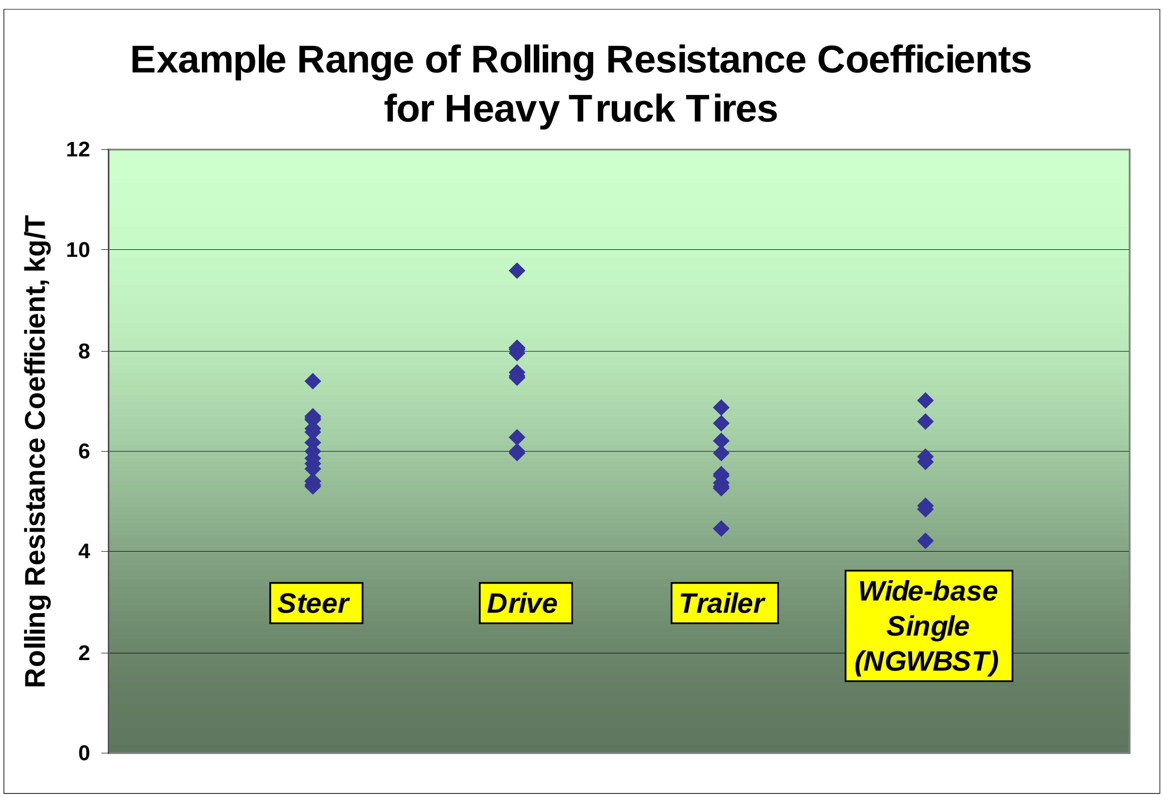
Technology	EPA Bin	Drag Co-efficient.	% Drag Reduction	%FC Reduction*	Cumulative FC %
Classic Cab & Trailer	1	0.790	Base	Base	100
Aero Cab I		0.742	6	1.56/ 1.70	98.44/ 98.3
Aero Cab II	2	0.698	6	1.56/1.70	96.9/ 96.6
Cab Gap Extender		0.650	3	0.78/ 0.85	96.1/ 95.8
Tractor Fairing/ Skirts		0.624	4	1.05/1.15	95.1/ 94.7
Aero Cab III		0.599	4	1.05/ 1.15	94.1/93.6

*Low roof/ mid-roof

Hence, for a non-van body tractor trailer on the same long haul cycle, the maximum benefits are only on the order of 6% from the tractor. Aerodynamic benefits for devices for flatbed trailers and tankers have not received much attention but some modest benefits may be available. EPA assumes that 40% of day cab tractors are in Bin 1 while 60% are in Bin 2. We use this data since we do not have independent data on the baseline for these vehicles.

4.2 ROLLING RESISTANCE REDUCTION

The deformation of the tire as it rolls results in rolling resistance losses, and rolling resistance is proportional to the load on the tire. The rolling resistance coefficient (RRC) is the energy dissipated by the tire per unit distance normalized by the load on the tire, and is currently about 7 kg/ton, or 0.007. Information from tire manufacturers suggests that the RRC has declined by about 1.4 percent per year since the introduction of truck radial tires around 1960 with an RRC of about 0.14, although the rate of decline has not been uniform through the period. Unfortunately, little data on actual tire RRC values are publicly available to obtain the exact average and distribution, but sample data provided by Michelin is shown below in Figure 4-8. The figure suggests that steer and trailer tires have an approximate RRC of about 0.006 while drive tires are higher at about 0.008. More importantly, the figure shows that actual in-use tires show wide disparities in RRC, up to 40 percent between the best and worst, but there is little information on other tire variables which may be compromised by reduced RRC such as traction or durability.



The use of higher RRC tires on the drive axle does suggest that some compromise between traction and RRC is possible for a given level of technology. For example “rib” tires with straight tread grooves have lower RRC than “block” or “lug” tread designs but also have lower traction and are typically used on trailer axles. However, there is significant variation in RRC even within specific axle groups and tire tread designs; for example, some newer drive tires with continuous shoulder ribs can have lower RRC than trailer tires. In addition, the weight loads on the axle groups are different, and this leads to different sensitivity to RRC reduction. For example a properly loaded 5-axle tractor trailer will have 42 $\pm$ 2% of the load on each dual axle group and 16 $\pm$ 1 % on the front axle, but because of the higher RRC tires used on drive axles, they can account for about 50% of tire energy loss with the trailer axles accounting for 35% and the front axle accounting for 15%.

The EPA SmartWay program certifies tires that meet a maximum RRC level, which are currently specified as 5.8, 7.3 and 5.2 kg/ton for the steer, drive and trailer axles, respectively. Anecdotal information from truck manufacturers suggests that about half of all trucks are using tires that meet or exceed these specifications as of 2009, but the picture on trailer tires is less clear. These values may be close to the averages for Class 8B vehicles (tractors). If the averages decline at the historic rate of 1.4% per year, then the 2020 values will be 5 and 6.25 kg/ton respectively, which are equal to the lowest values shown in Figure 4-8. There appears to be no specific lower limit for 2025 proposed by tire manufacturers by axle type but the historical rate suggests a reduction of 20% to 4.64 and 5.84 kg/ton, though some studies such as those by NESSCAF and TIAX have asserted a lower value of 4 to 4.5 as feasible before 2020 for all axles.

The “Wide Base Single” tire has been offered by Michelin since the 1980s, and a New Generation version has been offered since 2000. Michelin has claimed that this tire can replace the dual tires employed on drive and trailer axles and their Single tire has 20 percent lower RRC than the best dual tire option. Current data shows some super single tires near the 4.0 kg/ton value, but it is not completely clear if the test methods to determine rolling resistance are identical across manufacturers. In addition, the lower tire and rim weight can save 700 pounds with Aluminum rims, and possibly more with steel rims, and net cost on a new truck is lower due to the savings on the rims. In spite of these claimed advantages, the wide base single tire technology has achieved a market penetration of under 10% in 2009 according to truck manufacturers. One reason is that these tires do not offer “limp home” capability in the event of a tire failure while dual tire system could provide such capability in emergencies. Specific truck manufacturers also stated that some fleet owners experienced very little fuel savings when switching from low rolling resistance dual tries to wide base single tires. Finally, some states do not allow such tires on oversize/ overweight loads, so truck owners are cautious about using these tires. However, the wide base singles appear to reduce RRC by an additional 20 percent over a similar technology regular tire.

The effect of a 10 percent RRC reduction is readily derived from the sensitivity coefficients shown in Table 2-1. For a long haul truck, a 10 percent RRC reduction results in 3.5% reduction in fuel consumption at constant engine efficiency, but engine efficiency decreases slightly due to the lower average load so that a slightly lower number is expected. On a regional route, the same 10 percent RRC reduction results in a 2.15 percent fuel consumption decrease at constant engine efficiency. Michelin also provided data on the measured values from reducing RRC by 20 percent as shown here:

Heavy Truck (40t) 12.0l Diesel engine	Fuel Consumption		Fuel Savings	Percent
	CRR=5.5kg/t	CRR=4.5kg/t		
Sub Urban Use – half loaded	16.53 gal/100mi	15.98 gal/100mi	0.55 gal/100mi	3.3%
Regional Use – half loaded	15.13 gal/100mi	14.53 gal/100mi	0.59 gal/100mi	3.9%
Long Haul Use – half loaded	12.62 gal/100mi	11.94 gal/100mi	0.68 gal/100mi	5.4%
Sub Urban Use – full loaded	21.29 gal/100mi	20.57 gal/100mi	0.72 gal/100mi	3.4%
Regional Use – full loaded	19.76 gal/100mi	19.04 gal/100mi	0.72 gal/100mi	3.7%
Long Haul Use – full loaded	14.92 gal/100mi	14.02 gal/100mi	0.89 gal/100mi	6.0%

The regional cycle full loaded data shows a 3.7% decrease as opposed to the expected 4.3% and the long haul cycle shows a 6 percent decrease in fuel consumption as opposed to the 7% predicted, indicating that efficiency losses in the engine reduce the expected value by 15% in both cases (from 7 to 6 and 4.3 to 3.7). Hence, the anticipated 20% reduction in RRC between 2009 and 2025 should result in a 6% decrease in fuel consumption on the long haul cycle and a 3.7% decrease on the regional cycle. The

Michelin data also shows the reduced effect of RRC when the truck is not fully loaded, and the benefit of RRC reduction is reduced by 10 to 15 percent when moving from full load to half load. On the vocational truck cycle, the benefits of RRC reduction are quite small, with a 10 percent reduction yielding a maximum 0.8% fuel consumption benefit and an expected 0.68% benefit.

Costs of reduced rolling resistance are difficult to estimate since many tire attributes vary simultaneously. Cost increments estimated by TIAX are based on super single tires but appear to include the cost of aluminum rims (which reduce weight but not rolling resistance). According to manufacturers, the tires with Smart-Way specification typically cost $50 to 100 more per tire on average than uncertified tires and we have utilized this number ($75 $\pm$ 25) for a 10% RRC reduction, and $150 for a 20% RRC reduction per tire. Costs of the Single Wide Base Tire are small to negative if the cost of the rims are included and hence all of the cost is associated with the hedonic cost of uncertainty about limp home potential and resale value.

4.3 WEIGHT REDUCTION

The reduction in truck empty weight can have a beneficial effect on fuel economy or on the payload specific economy (payload ton miles per gallon) if the weight reduction is offset by increased payload. However, only a small fraction of trucks operate at the GVW limit at any given time and it appears likely that about 90 percent of trucks will have a fuel economy benefit from weight reduction. Weight affects both the inertial energy lost to the brakes and tire rolling resistance. With increasing speeds, the inertial loss component goes down as the tire component increases so that the sum of the two is near constant between 20 and 50 mph at 45 to 48%. At very low speeds (~5mph) the inertial component is dominant, but at speeds higher than 50 mph, the aerodynamic component becomes the largest single source of energy loss.

For a typical tractor trailer unit, the tractor (day cab) weighs about 14,000 pounds and the 53 foot steel trailer weighs about 13,000 pounds. Sleeper cab units are about 3000 to 4000 pounds heavier, so that the tractor-trailer combination weighs 27,000 to 31,000 pounds. Typical operating weight is about 75,000 pounds, so that a 1000 pound weight reduction is a 1.33% decrease of total weight but a 3.4% decrease of empty weight. As noted, weight accounts for 47.5% of energy use on the long haul cycle and on the regional cycle, so that a 1000 pound weight reduction corresponds to a 0.64% fuel economy increase at constant engine efficiency or a 0.54% increase with a 15% efficiency loss factor as for tires. This number corresponds well with data reported from SmartWay (which reports impacts from 0.4 to1.0 percent) and the NESCCAF simulation study which reports 0.5%. The Aluminum Association also reported that a 10 percent empty weight reduction corresponds to a 1.6% fuel economy benefit which is proportional to the benefits we derived for the 3.5% reduction.

Medium-duty trucks in Class 6 and 7 weigh about 14,000 ± 1000 pounds for a van body unit and operate at 24,000 pounds (class 6) to 30,000 pounds (class 7) loaded weight. Hence, a 500 pounds. weight reduction corresponds to a 2.1% weight decrease for a Class 6 truck to a 1.7% reduction for a class 7 truck, with fuel economy impact of about 1% and 0.8% respectively. Data from manufacturers suggest that the 0.8 to 1 percent range is appropriate for this level of weight reduction.

Weight Reduction Through Material Substitution

Weight reduction is possible both through improved design and through the use of alternative materials, notably composites and/or aluminum. It is now common for cabs to have composite fenders, hood and aerodynamic aids such as the roof deflector and side flares. (Of course, the aerodynamic add-on devices add weight). However, most structural parts are still made of steel. Widespread use of high strength steel and weight efficient design can reduce weight; for example, MAN has introduced the new TGX series that saves 200 to 270 pounds relative to the older TGA series through improved design and use of high strength steel. The replacement of the twin leaf springs for the front axle with a single parabolic leaf alone resulted in a 100 to 120 pounds. weight saving. The use of HSLA in suspension components in the rear axle saves about 50 to 60 pounds

In addition, the 12L engines now common in most long haul trucks save about 300 to 400 pounds relative to the older 15L engines. The newest generation of trailers uses composites and high strength low alloy (HSLA) steel and are 1000 to 1500 pounds lighter than older all steel trailers. At the same time, we note that many of these improvements are now incorporated into the majority of new trucks and are hence in the baseline.

For analysis purposes, we have separated truck empty weight reduction into four steps:

- A 5% weight reduction from weight efficient design and extensive use of HSLA steels as well as a smaller displacement engine. Most trucks introduced in the 2007+ time frame already incorporate these improvements although the state of the trailer market is less well understood.
- A 10% weight reduction from the use of composites for body closures, floor panels and exterior panels, as well as aluminum in some castings and forgings. Some Class 8B trucks that emphasize weight reduction already offer these improvements in new models
- A 15% weight reduction from aluminum or composite use in structural members such as the frame rails. Aluminum frame rails can save 900 to 1000 pounds if used on both tractor and trailer in a Class 8B truck, for example, and are offered in specific applications like a fuel tanker which operates at maximum allowable GVW.
- A maximum 20% weight reduction with a highly intensive weight reduction design employing both aluminum and composites. This is based on inputs from manufacturers, who see this level as technically achievable but not cost-effective now.

Each step in the weight reduction ladder corresponds to 600 to 700 pounds weight reduction for a Class 6/7 van body truck and a similar level of weight reduction for the tractor and trailer (each). In a recent analysis of light duty vehicle weight reduction, we have estimated the cost of material substitution per pound saved as $0.75. $1.50, $2.50 and $4 per incremental pound saved in each step. For a class 8 tractor, this would amount to $490, $1470, $3100 and $5700 respectively with similar amounts for the trailer.

5 FUEL SAVINGS FROM OPERATIONAL IMPROVEMENTS

5.1 OVERVIEW

Unlike light-duty vehicles, there is significant potential to reduce fuel consumption by increasing the operational efficiency of moving goods. These improvements can be summarized as follows

- reducing empty backhaul
- preventing over-speeding on the highway
- use of adaptive and predictive control
- improved driver training to drive in a fuel efficient manner
- maintaining proper tire pressure
- using double trailer combinations or longer trailers
- mode shifting from road to rail (inter-modal transport)
- Idle reduction

These operational items and their potential benefits are **not** the focus of this report but are mentioned here, as many analyses of fuel savings from heavy-duty trucks have combined operational savings with technology based savings. Only idle reduction can be facilitated with technology and considered in more detail in Section 5.3, but all other issues are summarized below.

5.2 SUMMARY OF POTENTIAL SAVINGS FROM OPERATIONAL IMPROVEMENTS

Reducing empty backhaul for heavy-heavy duty trucks can be achieved by better load and route matching but there is obviously an irreducible minimum since some amount of empty mileage is necessary as the delivery point and pickup of new loads will never occur at the same location. The 2002 VIUS data shows that empty backhaul accounts for

33 percent of VMT and about half that percentage of fuel consumption since trucks are substantially more fuel efficient when empty. Since 2002, there has been a proliferation of private load matching services and route optimization services based on the internet and on GPS based truck position sensing. Anecdotal evidence suggests that empty backhaul has declined since 2002 to less than 25%, and that load clearing market is already quite efficient. Hence, further fuel savings from reducing empty backhaul may be quite small and probably account for less than 5 percent fuel saving potential.

Preventing **over-speeding** on the highway has been shown to provide significant fuel savings. Reducing the speed from 70 mph to 65 mph (or 7.1%) results in a 6 percent fuel economy improvement. For a vehicle operating 100,000 miles per year at a base fuel economy of 6 mpg, fuel cost with diesel at $3 per gallon is $50,000 annually. Hence, a six percent fuel economy improvement saves about $2830 annually. Unfortunately truck productivity is also reduced since the distance traveled per day is reduced. Trucks do not operate at 70 mph all the time and assuming a peak to average speed ratio of 1.75, the reduction of peak speed by 7.1% will reduce truck productivity by 4.1%. A HHDT typically produces revenues of $180,000 to $250,000 per year implying a productivity loss of $7350 to $10,200, substantially higher than the fuel savings. This is the major reason why truckers speed; the economic incentives are too strong even at higher fuel prices. We do not anticipate any fuel savings from voluntary speed reductions. However, the EPA has proposed providing credits for hardwired speed limiters set at 63 mph or 60 mph. The credit provided for sleeper cab equipped trucks is quite large due to the EPA assumption that 85% of their VMT, these trucks operate at 65mph constant speed.

Driver training can have a significant impact on fuel economy on-road. The American Trucking Association (ATA) Maintenance Council estimates that the best drivers compared to the worst drivers can improve fuel economy by up to 35% but this is an extreme comparison; other studies have estimated impacts in the 5% to 15% range. In addition to limiting speed and idling time, drivers can improve fuel economy by improved gear shifting, acceleration practices, route choice and use of accessories. Due to the overlap with speed and idling issues considered separately (which accounts for much of the fuel economy benefit), we selected 4% as a possible maximum benefit from driver training, and have assumed that about 50% of drivers (mostly employed by large fleets) have already had the training. Costs of driver training programs are estimated at $1400 based on data from ATA.

Maintaining proper tire pressure improves fuel economy since under-inflation by 10psi increases rolling resistance by 7% which reduces fuel economy by about 1.5 to 2% if all tires are under-inflated by this amount. Of course, under-inflation may vary across tires on a given truck, and EPA has estimated from limited survey data that the net average of proper inflation is to increase fuel economy by 0.6% for the fleet as a whole. New tire pressure monitoring systems are available for the approximate cost of $40 per tire + $100 for the monitoring system.

Shifting to larger trailers or using combinations of trailers called long combination vehicles (LCV) is always more efficient in terms of fuel use per ton-mile of payload transported. While this is widely recognized, many states and local areas restrict the use of multiple trailers that involve the use of two or three trailers of differing lengths (depending on state) that are currently used in some states. Indeed, the trucking community refers to these as “Turnpike doubles” or “Rocky Mountain doubles” and “triples”. LCV use is governed by federal law. Prior to 1991, states could set their own laws with regard to trailer length maximums and combination maximums. After a handful of (western) states starting increasing the maximum trailer limits the federal government stepped in and has governed the maximums for the interstate highway system, effectively governing all use. However states that had already increased their maximums were grandfathered into the new system and the old maximums are still allowed in those states. An allowed double is a combination of two 28-foot trailers, but this has limited application since it isn’t much bigger than a single 53-foot trailer that is standard. It is used for specific operational requirements where an operator will need to drop one trailer and carry the next to another destination (for example, Fed-Ex or UPS).

The use of many double combinations increases payload based efficiency by 12 to 25% based on measured values, but are often opposed based on safety grounds as it makes passing on narrow roads much more hazardous, and on access due to maneuverability issues. However, a change in federal law can widen usage to major routes, and assuming that the shortest double trailer combination (the Rocky Mountain double) is allowed, fuel usage can be cut by 15% on approximately 60% of HHDT. This is a “zero cost” option if social and safety issues are not considered

Inter-modal freight has received wide attention in recent times. It is widely known that goods movement by rail or barge is much more energy efficient and rail can use one-tenth of the energy of trucks if the routes are identical and delivery is not time constrained. It is very difficult to generalize this to any specific load and route, since the route circuity on rail and the distance of the rail head from the pick up and delivery points strongly affect these comparisons of energy use. Increased use of barges is, of course, limited by available waterways. Road-to-rail has been increasing significantly for goods (typically commodities such as grain, ores, fertilizer, cement, etc.) where the market forces do not place a premium on time sensitivity, and the 2002 VIUS shows that bulk goods and commodities account for only 4% of trucking payloads. Hence, it appears that the market for road-to-rail is quite efficient and further significant movement in this direction may not result in large fuel savings.

5.3 IDLE REDUCTION

Idle reduction has received considerable attention form EPA and CARB with reference to criteria pollutants, but is also an energy issue. Surprisingly little data exists on the actual extent of long idles in practice; the EPA estimate of 8 hours a day for 300 days a year for all HHDT appears to be very much higher than any trucking industry estimate. Many long distance trucks do keep their engines on at night when the trucks feature a sleeper cab to provide space conditioning, but some trucks are kept running under very cold winter conditions because of problems starting a large diesel engine in very cold weather (typically below -10 C).

There are several technology options to reduce fuel use during idling including

- Direct-Fire Heaters, which heat the cab and engine using a small flame and a heat exchanger. This technology has only around 5% market penetration in US vs. 55% in Europe.

- Auxiliary Power Units (APU), which are a secondary combustion engine connected to a generator to power electrical systems and provide heat. They have near zero market penetration due to concern about overloading existing wiring systems and retrofits rendering void the truck's warranty.

- Automatic Engine Idle Systems, which run the engine only to maintain set cabin temperature and battery voltage, and can automatically shut off and restart the engine to minimize fuel use. They are offered as an option of new truck purchases from some manufacturers but some drivers can find engine restarts disruptive while sleeping. They are currently installed in trucks that account for 7-8% of VMT.
- Truck Stop Electrification, which taps the electrical power grid to power the truck's auxiliary units while at overnight stops. This technology requires a properly equipped station with a "shore power" port as well as additional wiring and equipment on the truck. Stations are rare with implementation suffering from a 'chicken or the egg' problem as stations don't see a market until enough trucks are equipped, while the added cost of the equipment for trucks does not pay back without a sufficient station network.
- Advanced Truck Stop Electrification which provides cabin heating and cooling from an external source via air supply and return pipes as well as power outlets for driver accessories. A pilot project (IdleAire Technologies) charges $1.20 per hour to truckers and installs at stations at no fee to the station operators.

Based on the cost-benefit analysis shown below in Table 3-1, we have considered engine idle systems, direct fire heaters and APU power as possibilities for fuel conservation. Truck Stop Electrification is very cost effective but could require significant market intervention to make it widely available.

Table 3-1: Costs and Benefits of Idle Reduction Strategies

Technology	Initial Cost	Fuel Reduction Gallons	Fuel Reduction percent	Emission Reduction (kg) CO2	Emission Reduction (kg) Nox	Emission Reduction (kg) PM-10	Maint. Savings	Operating Charge	Payback Period (months)
Direct-Fire Heater	-$2,000	690	4.3%	7,000	121	N/A	$210	$0	19
Auxiliary Power Unit	-$7,000	1,320	8.1%	13,392	166	2.5	$336	$0	36
Automatic Engine Idle	-$1,250	900	5.6%	9,131	97	2.1	$168	$0	10
Plug-in TSE	-$2,800	1,800	11.1%	11,613	179	4.1	$336	-$745	15
Advanced TSE	-$25	1,800	11.1%	11,613	179	4.1	$336	-$2,880	2

Note: All costs reflect the perspective of the truck owner. Advanced TSE can provide services that may have to be paid
for separately, such as Internet access. The value/savings of such non-fuel related services is not reflected here.

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Most of the operational improvements are also not relevant for these classes of trucks except for the automatic engine idle and driver training related benefits. Of course, cost effectiveness for all technologies are quite different due to the different annual miles of travel and different use patterns but these are accounted for in the calculations shown in Section 6.

6 FUEL ECONOMY POTENTIAL AND COST EFFECTIVENESS ANALYSIS

6.1 OVERVIEW

This Section provides an integrated view of the fuel savings and costs possible from an analysis of scenarios of all truck technologies operating together on various truck weight classes, and different duty cycles. However, our detailed discussion of truck operating characteristics and technologies in the previous sections show that

- every weight class of trucks has a range of different truck types operating different duty cycles
- the current technology and fuel economy baseline for 2008/9 is not well understood
- costs of truck technology vary over broad ranges and by vehicle type.

Hence, the analysis presented in this section targets some specific functional areas where there are significant truck populations based on the VIUS survey data and allocates them to one of three duty cycles that are based largely on manufacturer inputs. In addition, baseline technology levels are based on manufacturer comments on sales in 2008/9. The cost issue was tackled by allocating technologies into broad payback categories that were more easy to determine than specific costs. The data and methodology employed to make these distinctions are described below.

6.2 NEW TRUCK SALES ALLOCATIONS BY CLASS AND APPLICATION

New heavy-duty truck sales have varied significantly over the last 5 years with the medium trucks in classes 5 through 7 varying form as much as 180,000 units to as low as 100,000 units. class 8 trucks sales have also varied form a high of 275 thousand units to a low of 128 thousand units during the period. These large variations were in part due to a "pre-buying" rush to beat the emission requirements for 2007 and exacerbated by the recession in 2008. We anticipate future sales of about 140,000 units in the 2012 to 2015 period for medium duty trucks and sales of 225,000 Class 8 trucks. About 30% of Class 8 units are straight trucks (class 8A) in the 40,000 to 60,000 pound GVW category primarily used in rough-duty applications like refuse haulers, agricultural goods carrier and construction support (all 3 axle trucks are over 33,000 pounds GVW). The remaining 70 percent of class 8 vehicles are tractor-trailer units with GVW over 60,000 pounds or class 8B, and these are typically the focus of most analyses due to their high annual VMT Such trucks are used in long haul and regional haul applications, with a relatively small percentage in rough duty and short haul applications. About 60% of these feature sleeper cabs and 70% have enclosed van bodies. The splits between cab type and body type for new trucks, based on industry information, is as follows as a percent of entire Class 8B fleet:

Cab Type		Sleeper	Day cab
Van body		50%	20%
Tanker		2%	4%
Flatbed/Dump		8%	16%

The VIUS survey data lists the typical radius of operation in steps of 0 to 50 miles, 50 to 200 miles and over 200 miles, and the percentage of Class 8B trucks in the longest radius of operation is only 17.1% but the 50 to 200 miles segment is at 34.1%, and the average annual VMT for the van body tractor trailer is 112,500 miles and 82,000 miles for each segment suggesting that the mid-range operations also may entail some sleeper cab use. Moreover, the percentages of the fleet are different from the percentages of new trucks in this class since trucks are used intensively in the first 4 to 6 years and then sold to second owners who use the more in regional and short haul applications. According to industry sources, the average VMT of sleeper cab equipped trucks is in the 95,000 ± 10,000 miles per year range while the annual VMT for day cab trucks is about 50,000 ± 10,000 miles across different body types. However, new vehicles less than 5 years old average 120,000 miles a year for the van body tractor trailer according to Vehicle Inventory and Use

Survey (VIUS) data, and this is relevant for many of the calculations of cost effectiveness.

Medium duty trucks (classes 6, 7 and 8A) have much lower annual VMT and van body trucks account for about 30 percent of all trucks according to both manufacturers and the VIUS data. About 70 percent of all trucks are used short haul applications while about 20 percent are used in regional haul, with the remainder in rough duty or vocational applications. In general the trucks used in regional applications average 20,000 miles a year while the trucks in short haul applications average only 12,000 miles per year. Vocational trucks average even lower annual VMT between 5000 and 10,000 miles per year. Trucks under 5 years old have somewhat higher average VMT at 28,000 miles per year for regional applications and 18.000 miles per year for short haul. These values are used to compute cost effectiveness to the buyer.

6.3 EVALUATIONS OF COST EFFECTIVENESS

The technology discussion in sections 3 and 4 pointed to the fact that technology costs were not well defined except in isolated instances, and also varied considerably in many cases by truck size and application. Hence, the development of a traditional supply curve of technology improvement to fuel economy versus cost is difficult to establish in a manner similar to that for cars. However, it is widely recognized that most long haul truck buyers demand a that costs of technology be paid back from fuel savings in 3 years or less so that full cost recovery is guaranteed within the period of first ownership which is usually 4 to 5 years before resale. It is not clear if the same payback requirement exists for medium duty trucks but manufacturers believed that this would be a useful approximation of market demand to examine payback periods of five years as being more representative. In addition, manufacturers were more willing to provide inputs on payback period in a general sense than to discuss specific cost data and industry discounting practices. Hence, we classified technologies by “payback period” where the payback was determined by the **undiscounted** value of fuel saved (at $3/ gallon) relative to the incremental price of technology into three categories:

- a period of 3 years or less implying that normal market forces would be sufficient for technology introduction

- a period of 4 to 6 years, implying marginal cost-effectiveness at current conditions, but some of these technologies could be adopted by the market if fuel prices increase or standards would require such technology
- a period greater than or equal to 7 years, implying technologies unlikely to be adopted by the consumer absent subsidies or severe market forcing conditions.

These payback periods correspond to the following approximate price limits per percent fuel savings for the three categories in different applications, and should be treated as indicators rather than as exact numbers:

Value of 1% Fuel Consumption reduction		Total VMT 3/6 years	3 year payback	6 year payback
Long haul tractor trailer		360K/600K	$1800	$3000
Regional Haul tractor trailer		180K/300K	$900	$1500
Regional haul medium duty		84K/125K	$280	$420
Short haul medium duty		60K/100K	$225	$375
Vocational trucks		30K/48K	$120	$190

As can be seen, there is almost a 15 to 1 range in allowable price increase per percent fuel savings depending on application, illustrating the difficulty of commenting on cost and feasibility without specific reference to a baseline and usage type. In addition, the same technology can be classified at very different levels of cost-effectiveness depending on application. These issues are addressed for the heavy –heavy and medium heavy segments separately in the following sections.

6.4 CLASS 8B HEAVY-HEAVY DUTY POTENTIAL

As noted in Section 6.2, the long-haul and regional haul segments of the Class 8B fleet account for most of the population and over 95% of fuel use in this segment.

Technologies have been organized into four categories: those necessary for emission control, those likely to be adopted by the free market (3 years or less payback), marginally cost effective technologies (4 to 6 year payback) and cost-ineffective technologies. Drive train and body technologies are shown in the two tables below.

Table 6-1 shows the drive train technology improvements over the 2008 – 2017 and 2008 – 2025 time frames. The 2010 introduction of urea/SCR has a very significant effect in the short term with emission control related technology providing a 5.4% reduction in consumption by 2017 and a 9.2% related reduction by 2025 assuming constant emission standards. The non urea emission control system is expected to result in a fuel efficiency loss of about 2.5 to 3 percent relative to the urea/SCR system and the route also precludes mechanical turbo-compounding due to the sequential turbo requirement, although organic Rankine cycle based heat recovery will be possible Urea consumption is at about 2 to 2.5 percent the diesel consumption rate. Hence, our analysis shows that the non-urea route could be competitive in regional haul category where mechanical turbo-compounding produces very small benefits, as long as urea prices are higher than diesel fuel prices (they were almost $6 per gallon recently). However, it is less competitive in the long haul category, at least for the short term when mechanical turbo-compounding is widely introduced, but may be competitive if the Rankine bottoming cycle is introduced. It is also notable that the free market forces will likely bring about half to two thirds of the total drive train improvements possible.

The benefits of reducing truck tractive energy requirements from drag, weight and rolling resistance reduction are more complex in terms of cost effectiveness. Classification of many improvements into payback categories is very problematic due to three issues. First, there are many more trailers than tractors, and the registered population ratio is about 2.8, but this masks a lot of variability around the average for individual fleets. In addition, there are reportedly a large number of lightly used old trailers, so that newer trailers may have a much larger fraction of miles traveled. We have assumed an "active trailer" to tractor ratio of 2 to estimate costs and effectiveness of technology applicable to trailers. Second, many devices have operational issues and concerns that has prevented significant market penetration, and we can associate this with a hedonic cost that must be added to the real cost. Third, the effectiveness of some aerodynamic aids on trucks with

Table 6-1: Potential Class 8B Fuel Consumption Reduction (%) from Drive Train Technology

		2017		2025	
		Long haul	Regional	Long haul	Regional
2500/3000 bar FI		0	0	1.0	1.0
Seq. Turbo +downsize		0	0	0.5	1.0
Urea/SCR		3.0	2.0	5.0	4.0
Cooled EGR		1.0	1.0	1.5	1.5
Closed Loop FI		1.5	1.0	3.0	2.0
Emission Control Total with/ without urea		**5.4/ 2.5**	**4.0/ 2.0**	**9.2 / 5.9**	**7.3/ 5.4**
Variable valve actuation		-	-	1.0	1.0
Mech. Turbo-compound		2.5	-	3.0	-
Engine Friction		1.0	1.5	1.5	2.2
12-speed + Direct drive		1.5	1.0	1.5	1.0
Engine+ axle lubricants		0.7	1.0	1.0	1.5
Improved Accessories		0.5	0.8	0.7	1.0
3 year payback tech.		**6.05/ 3.65**	**4.25**	**8.4/ 5.6**	**6.55**
Mech. Turbo-compound		-	1.3	-	1.5
Electric Acc. Drive		1.5	2.2	1.3	2.0
Automated Manual Tran.		3.0	5.0	3.0	5.0
Electric Turbo-compound or Organic Rankine		2.5	-	3.5 or 6.5 w/o urea	3.3 w/o urea
4 – 6 year payback tech,		**6.85/4.45**	**8.3**	**7.6 / 10.5**	**8.2 /11.05**
Electric Turbo-compound		-	1.2	-	1.8 w/ urea
Hybrid 50kW drive		3.5	7.0	4.5	9.0
>6 year payback tech		**3.5**	**8.1**	**4.5**	**10.65/ 9.0**
Total Potential With/ without urea		**20 / 13.3**	**22.5 / 18.9**	**26.6 / 24.1**	**29.0 / 28.45**

non-van body trailers is not well understood and we have the used same benefits or aerodynamic cabs and trailer skirts for both body types as a first approximation. The estimation of hedonic cost is simply based on the classification by payback and current market share. For example, the use of trailer skirts at a cost of $1500 to 2000 to produce a 3 percent fuel consumption reduction is cost effective in a 3 year time frame for long haul trucks (after accounting for 2 trailers per tractor) but actual market penetration is low at around 5%. This would correspond to a 5+ year payback so that the hedonic cost is approximately equal to the actual cost and total cost is double actual cost. The available technologies and payback classifications are shown in Table 6-2.

There are several major findings related to the data shown in Table 6-2. Unlike the fact that drivetrain technology benefits are comparable for the long haul and regional cycles, the benefits of body technologies are significantly higher for the long haul case than the regional haul case, and in the van body case relative to the non van body case. This is due to the fact that aerodynamic aids and reduced tire rolling resistance have a much larger effect at highway speeds than at city/suburban speeds, and many aerodynamic aids like the gap treatment and boat tail are applicable only to van body trailers. Second, the negative hedonic aspects of some technologies distort the standard computations of cost-effectiveness and many technologies that are relatively inexpensive have market penetrations that suggest high hedonic cost. Determining market resistance to these technologies in the future is still a challenge. Third, only about 40 to 45 percent of the total available benefit is in the 3 year payback category, suggesting that a majority of the benefits available will not be used in a free market scenario.

Idle reduction benefits outside of short term idle reduction from hybridization are not directly considered in the tables, since it applies only to the subset of long haul Class 8B vehicles with sleeper cabs where the HVAC is provided by engine power. As noted, anecdotal information has been used to estimate that idle fuel consumption for these vehicles can account for 8 to 10 percent of total fuel use, and the use of auxiliary power units or externally supplied air can reduce the fuel use by 50 to 100 percent. This finding is independent of engine energy used to overcome tractive force during driving and can be accounted for separately.

Table 6-2; Fuel Consumption Reduction from Class 8B Body Related Improvements (%) (Van body/ Non van body)

		2017		2025	
		Long haul	Regional	Long haul	Regional
Full roof fairing (50%)		1.9	1.25	1.9	1.25
Aero Cab II		2.3	1.50	2.3	1.50
Cab gap Extender		1.1	-	1.1	-
Aero Cab III		-	-	1.1	0.70
Rolling Resistance I		0.7	0.45	0.7	0.45
Weight Reduction I		0.8	1.0	0.8	1,0
Weight Reduction II		0.8	-	0.8	-
Rolling Resistance II		-	-	0.7	0.5
3 year payback tech.		**7.4 / 4.6**	**4.1 / 3.0**	**9.3 / 6.3**	**5.3 /4.0**
Weight Reduction II		-	1.0	-	1.0
Weight Reduction III		0.8	-	0.8	-
Cab gap Extender		-	0.7	-	0.7
Tractor Fairings		1.1	0.7	1.1	0.7
Additional Gap treatment		1.1	0.7	1.1	0.7
Trailer Side skirts		3.0	-	3.0	-
Wide base Single Tire		1.4	1.0	1.4	1.0
4 - 6 year payback tech,		**7.2 / 6.1**	**4.0 / 2.6**	**7.2 / 6.1**	**4.0 / 2.6**
Weight Reduction III		-	1.0	-	1.0
Weight Reduction IV		-	-	0.8	1.0
Trailer Side skirts		-	2.0	-	2.0
Trailer underbody		1.1	0.7	1.1	0.7
Boat Tail		1.9	1.25	1.9	1.25
>6 year payback tech		**3.0 / 0**	**4.8 / 3.0**	**3.7 / 0.8**	**5.7 / 4.0**
Total Potential		**16.7 / 10.6**	**12.4 / 8.5**	**19.0 / 12.7**	**14.3 / 10.3**

6.5 MEDIUM DUTY TRUCK TECHNOLOGY POTENTIAL

Almost all medium duty trucks in Classes 5 through 8A are straight trucks, with 2 axles (classes 5, 6 and 7) or 3 axles (class 8A). As noted in section 2, very few are used in long haul, and only a modest fraction, about 20 percent, are used in regional haul. The vast majority are used in urban locations or as vocational trucks in utility and municipal fleets or as buses. Due to the majority of such vehicles being used in low speed applications, it is likely that technologies better suited for high speed full load situations such as turbo-compounding or waste heat recovery may not be commercialized in the smaller displacement engines (6 to 10 liters), although there may be some models offering an optional turbo-compound versions.

Table 6-3 shows the benefits of drive-train technologies for vehicles operated on a regional cycle or city/ vocational cycle. The engine technology benefits are assumed to be similar for the city and vocational cycles as little data exists to accurately define the differences in engine technology benefits over a 15 to 20 mph cycle versus a 5 to 10 mph cycle with occasional high external power take off loads. However, the differences in hybridization benefits between the two cycles are recognized in this analysis. Although the benefits from engine technology alone are smaller for MDTs relative to the Class 8B vehicles, the net benefits from all drive-train technologies are higher than for Class 8B trucks due to the larger impacts of transmission and hybridization technology on the lower speed cycles.

Table 6-4 shows the benefits of body technologies for MDTs and the benefits on the regional cycle are comparable to those for Class 8B trucks, even though the aerodynamic benefits are smaller. However, the impact of body technologies is very small for trucks used in urban cycles or on vocational cycles since aerodynamics and rolling resistance are smaller parts of overall fuel consumption. This also minimizes the issues related to hedonic costs for trucks used in these applications.

Table 6-3: Potential MDT Fuel Consumption Reduction (%) from Drive Train Technology

		2017		2025	
		Regional	City/Voc	Regional	City/Voc
Seq. Turbo +downsize		0	0	1.0	1.5
Urea/SCR		2.0	1.5	3.0	2.0
Cooled EGR		1.0	1.0	1.5	1.5
Closed Loop FI		1.0	1.0	2.0	2.0
Emission Control Total with/ without urea		**4.0/ 2.0**	**3.5/ 2.0**	**7.3/ 4.4**	**6.3/ 4.9**
Variable valve actuation		-	-	1.0	1.0
Engine Friction		1.5	2.0	2.2	3.0
AMT (70% pen)		4.9	7.0	4.9	7.0
Engine+ axle lubricants		1.0	1.0	1.5	1.5
Improved Accessories		0.8	1.2	1.0	1.5
3 year payback tech.		**8.0**	**10.8**	**10.2**	**13.35**
Mech. Turbo-compound		1.3	0	1.5	0
Electric Acc. Drive		2.2	2.8	2.5	3.0
4 – 6 year payback tech,		**3.5**	**2.8**	**3.9**	**3.0**
Electric Turbo-compound		1.2	1.2	1.8	1.8
Hybrid 50kW drive*		12.0	20/30	15.0	24/35
>6 year payback tech		**13.1**	**21 / 31**	**16.5**	**26.35 / 36.1**
Total Potential Hybrid without urea		**25.2**	**32.9 / 40.3**	**29.5**	**41.1/ 48.9**

*Additional work is required to better characterize hybrid benefits and duty cycle dependence for trucks

Table 6-4: Fuel Consumption Reduction from Body Related Improvements (%) to Medium Duty Trucks

(Van body/ Non van body for Regional Trucks)

		2017		2025	
		Regional	City/Voc	Regional	City/Voc
Full roof fairing (50%)		1.25	-	1.25	-
Aero Cab II		1.5	0.4	1.5	0.4
Aero Cab III		-	-	0.7	0.2
Rolling Resistance I		0.45	0.15	0.45	0.15
Weight Reduction I		1.0	0.85	1.0	0.85
Weight Reduction II		1.0		1.0	-
Rolling Resistance II		-	-	0.45	0.15
3 year payback tech.		**5.1 / 3.9**	**1.4**	**6.2 / 5.0**	**1.7**
Weight Reduction II		-	0.8	-	0.8
Weight Reduction III		1.0	-	0.8	-
Wide base Single Tire		0.9	-	1.4	-
6 year payback tech,		**1.9**	**0.8**	**2.2**	**0.8**
Weight Reduction III		-	0.8	-	0.8
Weight Reduction IV		-	-	0.8	0.8
Side skirts		2.0	0.6	2.0	0.6
Boat Tail		1.25	-	1.25	-
>6 year payback tech		**3.2 / 2.0**	**1.4**	**4.0 / 2.8**	**2.2**
Total Potential		**9.9 / 7.8**	**3.6**	**12.0 / 9.7**	**4.6**

6.6 ABILITY TO MEET THE 2014/2017 STANDARDS

EPA has promulgated regulations for fuel economy and GHG emissions for heavy-duty trucks, with a voluntary standard for 2014 and a requirement for 2017. The standards are unusual in structure in that there is a separate standard for engines based on actual measured BSFC on an engine dynamometer, and a vehicle standard that assumes a "compliant" engine and models the effect of vehicle technologies using a simulation model. The effect of transmissions cannot be accounted for in the current set-up and hence EPA does not provide credits for transmission improvements. Vehicle technologies are accounted for in a discrete manner in which specific improvement types are bundled into "bins". The test cycles over which fuel economy compliance is evaluated is described in Section 2.5, and we noted the over-emphasis on the constant speed 55/65 mph modes for all trucks, and especially for sleeper cab equipped Class 8 trucks.

The engine standards are modeled in the regulatory analysis for the FTP and Steady State (SET) modes, and the required improvement for heavy-heavy duty engines to 2017 is 5% on the FTP cycle and 6.1% on the SET cycle, relative to 2010 baseline. In comparison, this analysis in Table 6-1 shows that a 6.05% improvement is possible within a 3 year payback(assuming that the 5% improvement related to urea/SCR implementation is included in the 2010 baseline) but this includes some transmission benefits equal to 1.7%. However, the benefits of turbo-compounding are much larger on the EPA cycle than our 2.5% estimate due to the high level of steady state operation, and we anticipate that technologies with 3 year payback will be adequate or nearly adequate to meet the 2017 standard. For medium duty engines, the standard requires an 8.6% reduction relative to 2010. Table 6-3 shows that up to 10.8% is possible for city/ vocational cycles, with 3 year payback but 7% is transmission related so that only 3.8% is possible form engine technology. In addition, we anticipate some improvements from emission control technology and adoption of a downsized sequential turbo engine that was not in the 2010 baseline for some engines that could provide an additional 1to 1.5% benefit. The shortfall would have to be made up with more expensive electric accessory drives, so that our estimate of cost of compliance for the medium duty engines would be higher than EPA's estimate.

On the vehicle side, the medium duty vocational trucks are offered only one option for improvement – tire rolling resistance reduction. The regulation allows credits for other technologies such as hybrids, but requires the manufacturer to demonstrate the benefits through actual testing. It is important to note that weight reduction and the use of the AMT, which figure very prominently in Table 6-4 for improvements are not considered in the EPA analysis.

In the case of long haul tractors, the regulations have several compliance options with aerodynamic and tire improvements, idle limiters and speed control. The benefits for these technologies are significantly higher than in our analysis due to the choice of the long haul cycle at steady state. Figure 6-1 shows the different compliance options for the long haul sleeper cab truck relative to the improvement required for 2017.

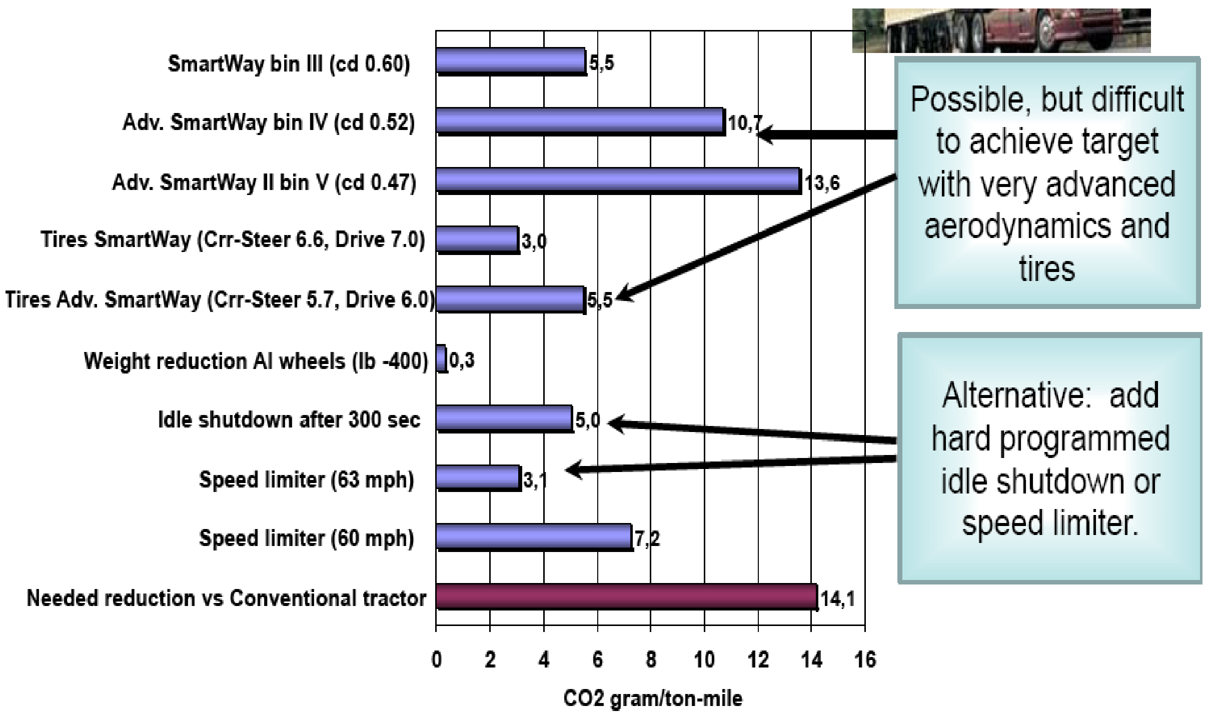

Figure 6-1: Technology Improvements for Class 8 Sleeper Cab Trucks for Compliance

The percentage reductions are very nearly similar to the CO_2 g/ton-mile reduction required since the baseline is 96 g/ ton-mile. The lowest drag aerodynamic tractor available today coupled with the lowest rolling resistance tires is enough for compliance but must be implemented across 100% of the fleet. Alternatives can include a 63 mph speed limiter which provides a 3.2% benefit, or idle shutdown after 5 minutes which provides a 5.2% benefit but these technologies carry substantial negative hedonic value that is not considered by EPA. Using the more realistic cycles, obtaining the required 14.7% improvement would require use of all technologies with a payback of up to 6 years from our calculations shown in Table 6-2. However, the overstatement of the benefit of the technologies shown in Figure 6-1 is a major factor allowing compliance.

6.6 SUMMARY AND CONCLUSIONS

The information in Tables 6-1 to 6-4 has been aggregated to provide forecasts of fuel consumption reduction by Class, Body Style and type of operation for the Class 8B trucks and the Classes 5 to 8A trucks in tables 6-5 and 6-6 for 2017 and 2025, respectively. The tables also show the cumulative technology benefit for fuel consumption reduction as a function of the payback period, with the column labeled ECT for emission control technology being independent of payback period as it is required by regulation. One of the unexpected findings from the analysis is that the total available benefit from technology is quite similar across all vehicle types (except vocational use trucks) at 30 $\pm$ 5 percent in 2017 and 39 $\pm$ 5 percent in 2025. However, the distribution of the benefits across payback period is quite different across the different combinations of weight class, body style, and use type.

The relative importance of hybrid technology, which is quite expensive, is also dramatically different, with hybrid technology accounting only for 11 percent of the total available benefit (not 11% absolute) in the Class 8B Long-haul Van body Truck to almost 70 percent of the total available benefit in vocational use trucks. Hybrid technology or trucks is still in its early development stages and refinement of this estimate is needed to better estimate the future potential especially to the 2025 period. Note that these estimates include the benefits of idle reduction in its definition of hybrid technology when the idle is part of the drive cycle, but does **not** include benefits of idle reduction associated with overnight use for sleeper cab trucks. The use of an auxiliary power supply unit or external HVAC supply can reduce fuel consumption by another 4 to 6 percent based on anecdotal estimates of annual use for overnight power.

The comparison of our results to those from the National Academy of Science's recent study of truck fuel economy is made difficult by the fact that the NAS study does not provide an explicit baseline or drive cycle associated with its percent consumption reduction estimates. In general, the NAS report includes the benefits of improved operational strategies and idle reduction; when their estimates are adjusted for the two effects, many of the numbers seem comparable. For example, the total benefit for tractor trailers is listed as 51 percent reduction in consumption with 6 percent from operational improvements another 4 to 6 percent from idle reduction (presumably overnight idle). This suggests technology benefits of about 40 percent on a comparable basis, which is very similar to our estimate. We are also less optimistic than the NAS on the pace of technology introduction and believe that these reductions may be feasible in 2025 rather than 2020, but even our estimate is an unprecedented rate of change for the truck industry.

In terms of the newly promulgated standards, the study shows the following:

- The use of 65/ 55 mph steady state cycles without any gradient to quantify fuel economy provides an incorrect picture of the real world benefits.
- The engine improvements required by EPA are those we consider likely to happen under free market forces for the heavy-heavy segment, but are aggressive for the medium duty segment
- Vehicle related improvements required for tractors in long haul operation emphasize drag and rolling resistance reduction, as well as speed limiters but their benefits are significantly overstated as a result of cycle choice.
- The benefits of weight reduction , transmission improvements and substitution of the AMT for an automatic are largely ignored by the regulation but are very relevant to the real world benefits, especially for medium-heavy trucks

APPENDIX A: DETAILED LISTING OF TECHNOLOGY IMPROVEMENT PROJECTIONS BY PAYBACK PERIOD

Regional

Wt. Class	Operating Range	Body Type		2008 MPG	ECT Benefit %	3 yr, Payback	6 year payback	Maximum Tech	Hybrid as % of max	Max. 2017 MPG
8B	Long Haul	Van (with urea)		6.00	5.40%	17.70%	28.86%	33.41%	10.48%	9.01
		Van (w/o urea)		6.00	2.50%	15.18%	26.68%	31.37%	11.16%	8.74
8B	Long Haul	Non-Van (with urea)		5.72	5.40%	15.21%	25.84%	28.43%	12.31%	7.99
		Non Van (w/o urea)		5.72	2.50%	12.61%	23.56%	26.24%	13.34%	7.75
8B	Regional	Van (with urea)		6.12	4.00%	11.85%	22.40%	32.11%	21.80%	9.01
		Van (w/o urea)		6.12	2.00%	10.01%	20.78%	30.69%	22.81%	8.83
8B	Regional	Non-Van (with urea)		5.66	4.00%	10.84%	20.36%	29.01%	24.13%	7.97
		Non Van (w/o urea)		5.66	2.00%	8.98%	18.70%	27.53%	25.43%	7.81
Medium	Regional	Van (with urea)		8.66	4.00%	16.18%	20.65%	33.26%	36.08%	12.97
		Van (w/o urea)		8.66	2.00%	14.44%	19.00%	31.86%	37.66%	12.71
		Non-Van (with urea)		8.82	4.00%	15.12%	19.65%	31.57%	38.01%	12.89
		Non Van (w/o urea)		8.82	2.00%	13.36%	17.98%	30.15%	39.80%	12.63
Medium	City	All (w/o urea)		8.00	2.00%	13.81%	16.89%	35.26%	56.72%	12.36
	Vocational	All (w/o urea)		6.70	2.00%	13.81%	16.89%	43.46%	69.03%	11.85

Table 6-5 2017 Projections by Vehicle Class and Application

Wt. Class	Operating Rang	Body Type		2008 MPG	ECT Benefit %	3 yr, Payback	6 yr. payback	Max. Tech	Hybrid % of max	Max. 2025 MPG
8B	Long Haul	Van (with urea)		6.00	9.20%	24.56%	35.31%	40.51%	11.11%	10.09
		Van (w/o urea)		6.00	5.90%	19.43%	33.08%	38.46%	11.70%	9.75
8B	Long Haul	Non-Van (with urea)		5.72	9.20%	22.07%	32.38%	35.94%	12.52%	8.93
		Non Van (w/o urea)		5.72	5.90%	16.77%	30.05%	33.73%	13.34%	8.63
8B	Regional	Van (with urea)		6.12	7.30%	17.96%	29.08%	40.25%	22.36%	10.24
		Van (w/o urea)		6.12	5.40%	16.28%	28.51%	39.77%	22.63%	10.16
8B	Regional	Non-Van (with urea)		5.66	7.30%	16.84%	27.06%	37.43%	24.04%	9.05
		Non Van (w/o urea)		5.66	5.40%	15.13%	26.47%	36.93%	24.37%	8.97
Medium	Regional	Van (with urea)		8.66	7.30%	21.92%	26.61%	41.17%	36.43%	14.72
		Van (w/o urea)		8.66	4.40%	19.47%	23.21%	38.45%	39.01%	14.07
		Non-Van (with urea)		8.82	7.30%	20.92%	25.67%	39.68%	37.81%	14.62
		Non Van (w/o urea)		8.82	4.40%	18.44%	22.23%	36.88%	40.67%	13.97
Medium	City	All (w/o urea)		8.00	4.90%	19.00%	22.06%	43.86%	54.72%	14.25
	Vocational	All (w/o urea)		6.70	4.90%	19.00%	22.06%	51.29%	68.24%	13.75

Table 6-6 2025 Projections be Vehicle Class and Application